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**De Rooij et al.**

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- (54) **PARALLEL CONNECTION METHODS FOR HIGH PERFORMANCE TRANSISTORS**
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**H01L 27/02** (2006.01)  
**H01L 27/082** (2006.01)  
**H01L 27/085** (2006.01)

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CPC ..... **H01L 27/0207** (2013.01); **H01L 27/082** (2013.01); **H01L 27/085** (2013.01); **H03K 17/122** (2013.01)

(58) **Field of Classification Search**  
CPC .... H03K 17/122; H03K 17/12; H03K 17/168  
See application file for complete search history.

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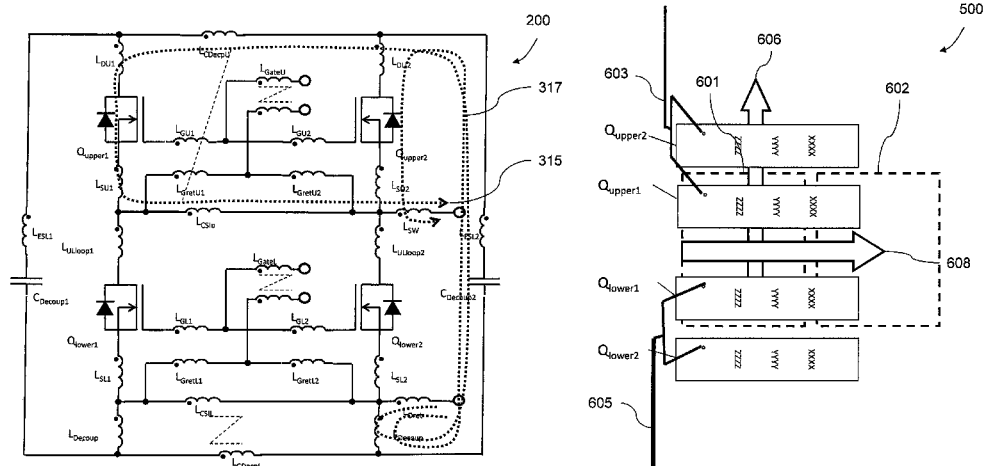
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(57) **ABSTRACT**

Parallel transistor circuits with reduced effects from common source induction. The parallel transistors include physical gate connections that are located electrically close to one another. The parallel circuits are arranged such that the voltage at the common gate connection resulting from transient currents across common source inductance is substantially balanced. The circuits include switching circuits, converters, and RF amplifiers.

**46 Claims, 36 Drawing Sheets**



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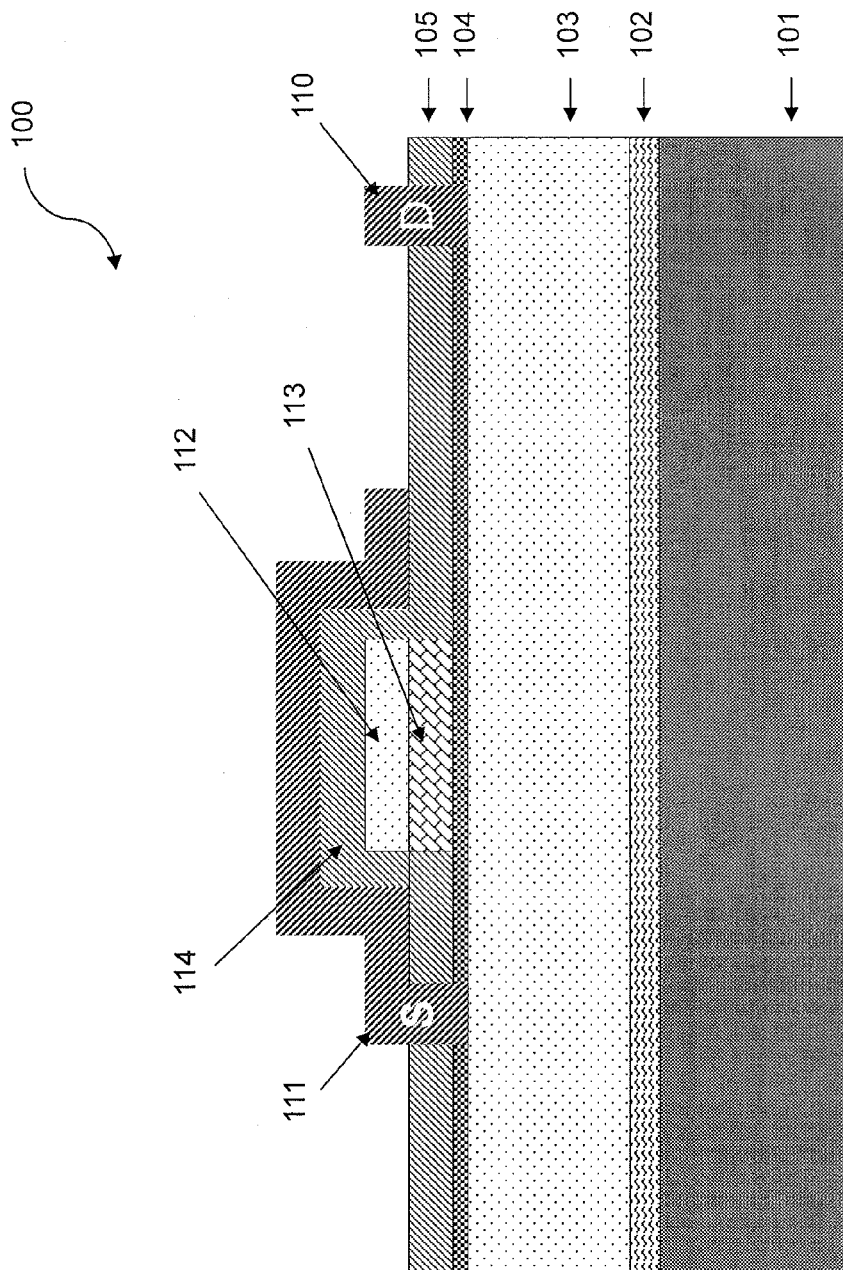
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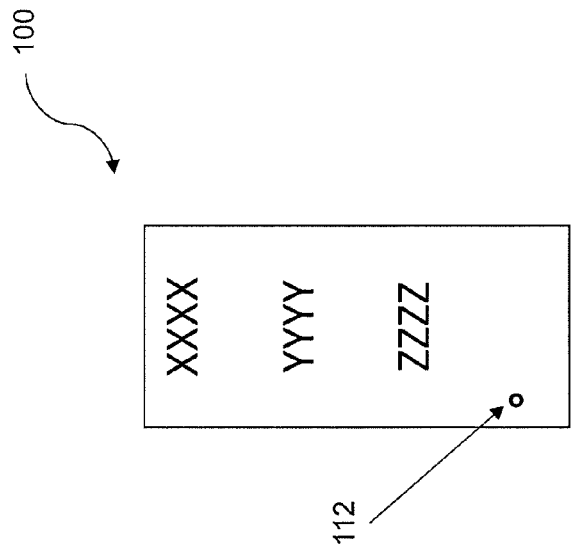
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FIG. 1A



Prior Art

FIG. 1B



Prior Art

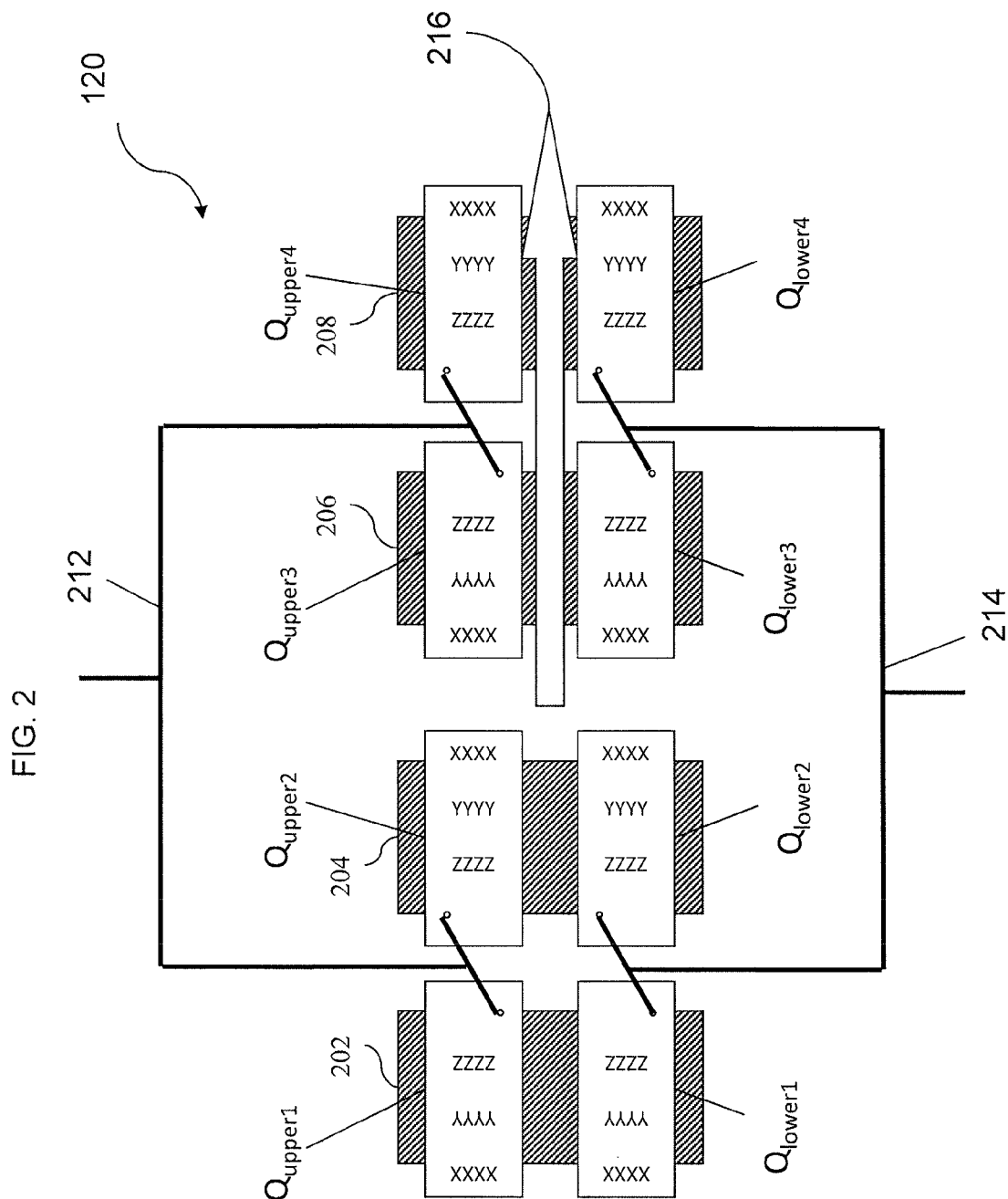


FIG. 3

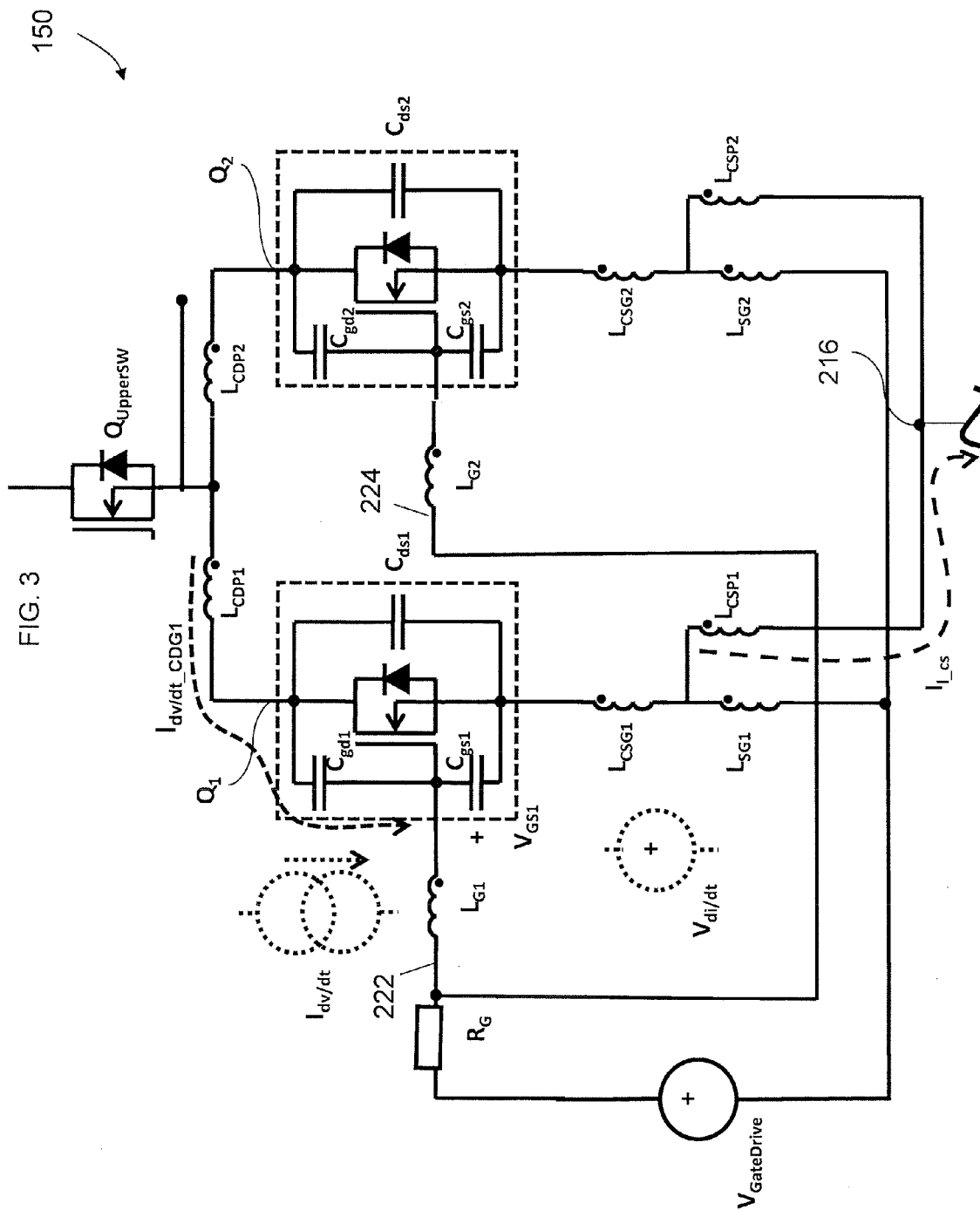


FIG. 4B

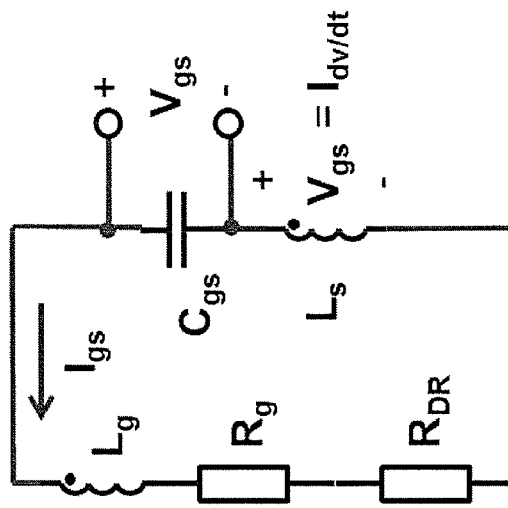


FIG. 4A

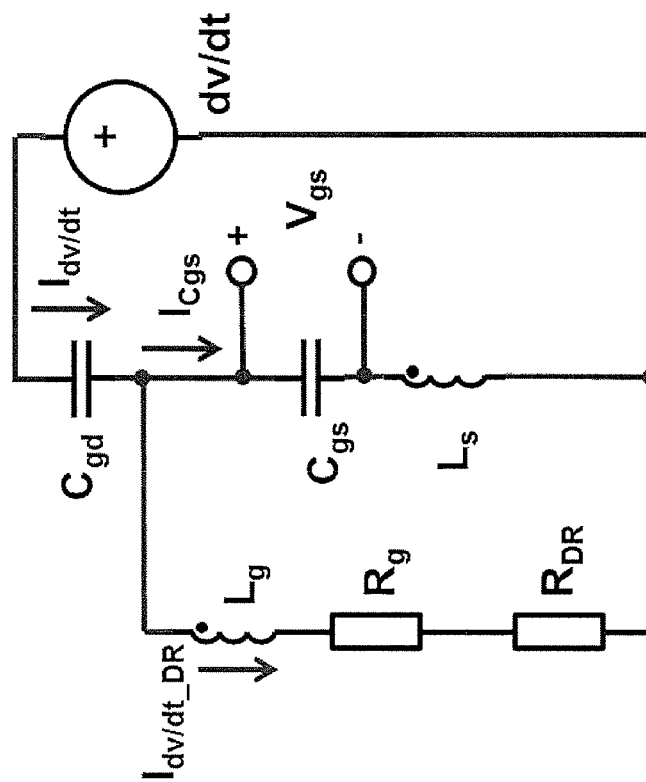


FIG. 5A

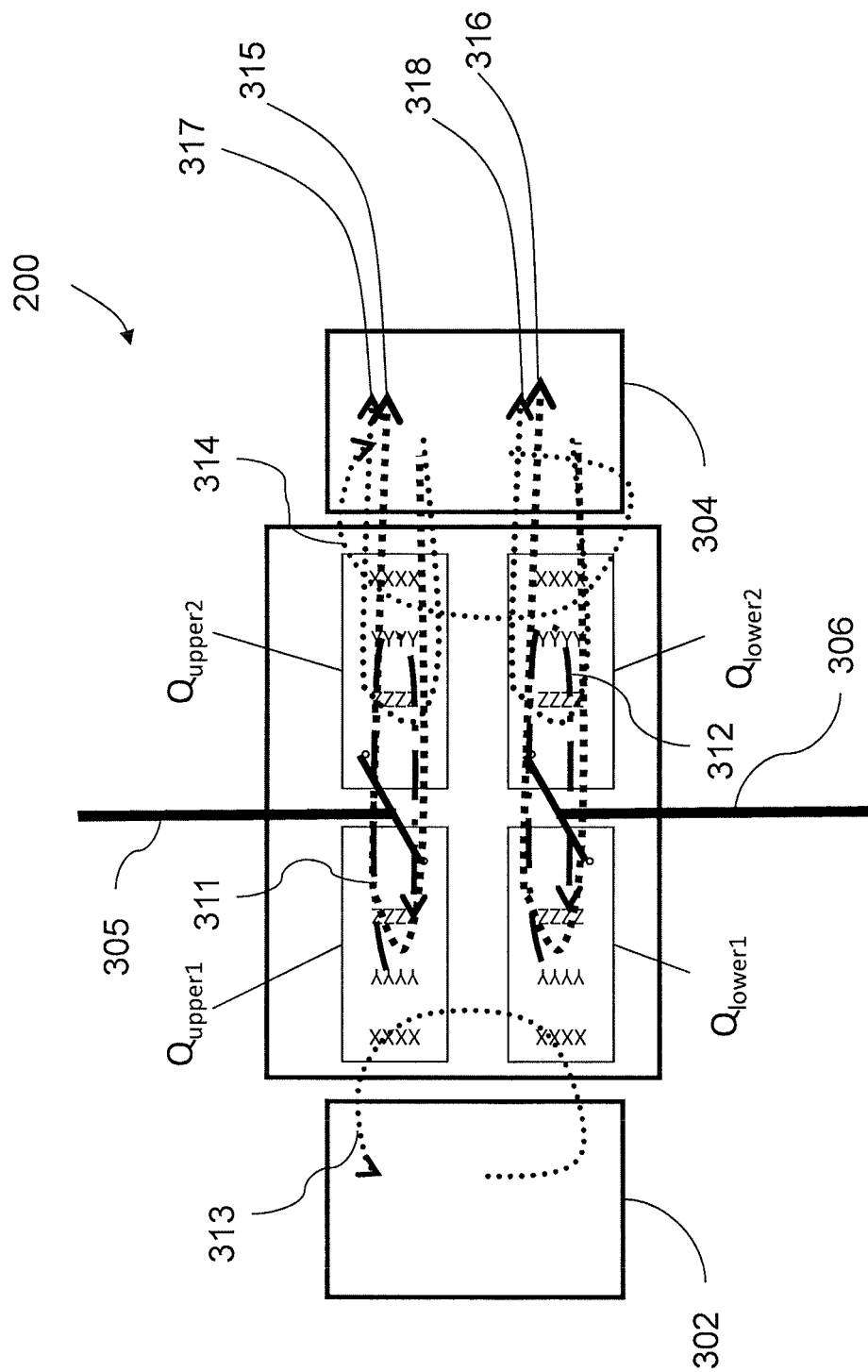




FIG. 5B

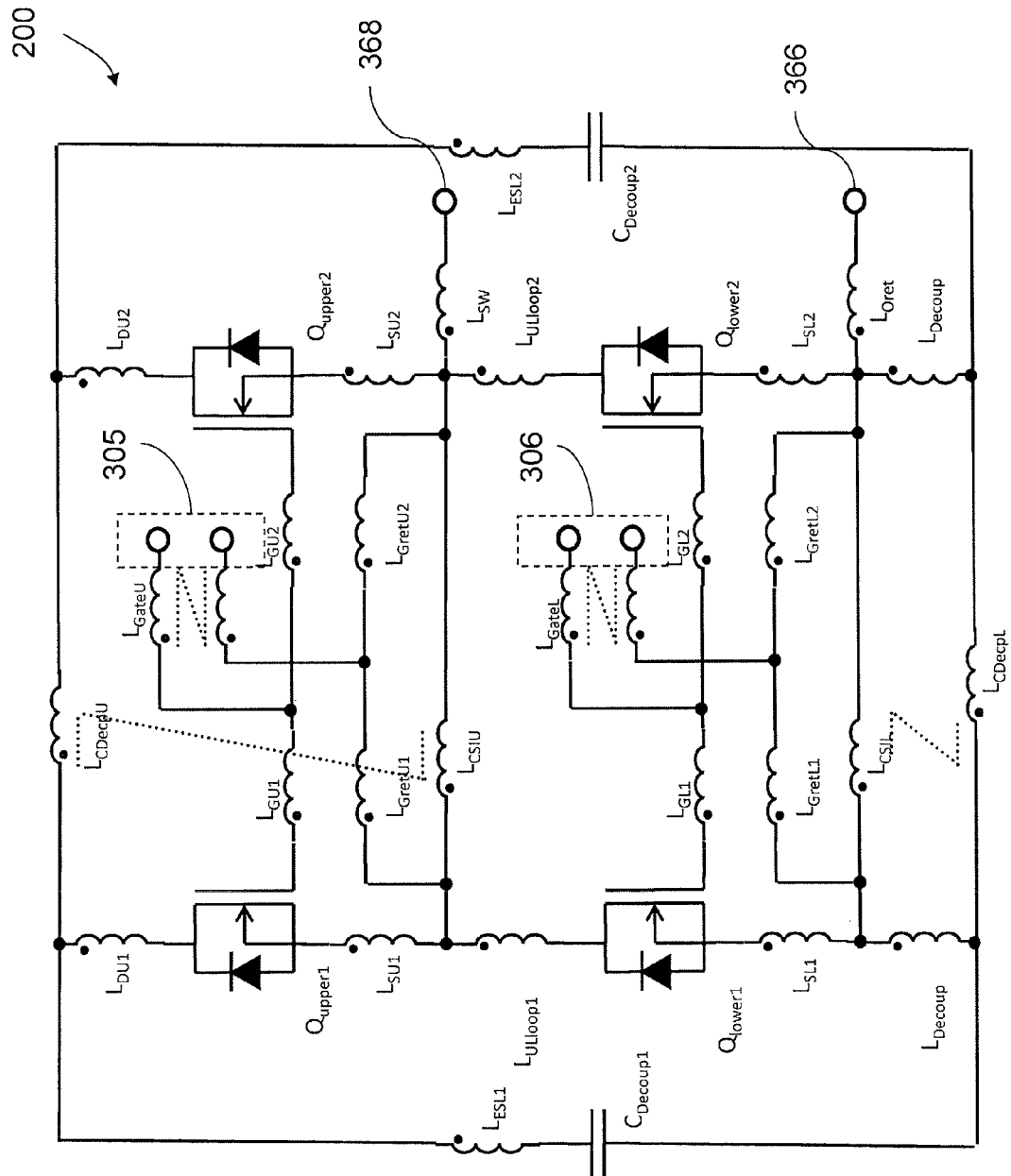


FIG. 6A

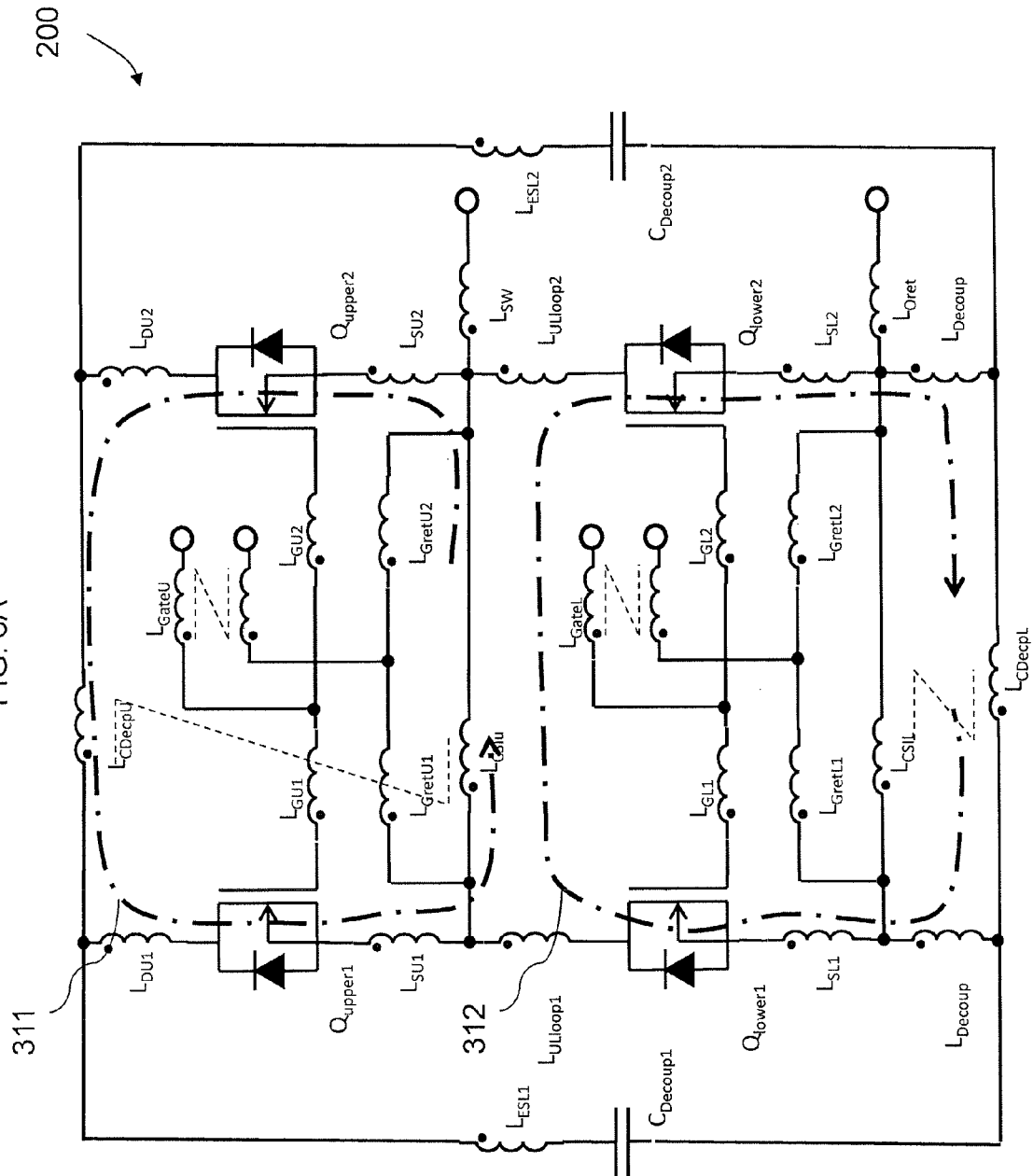


FIG. 6B

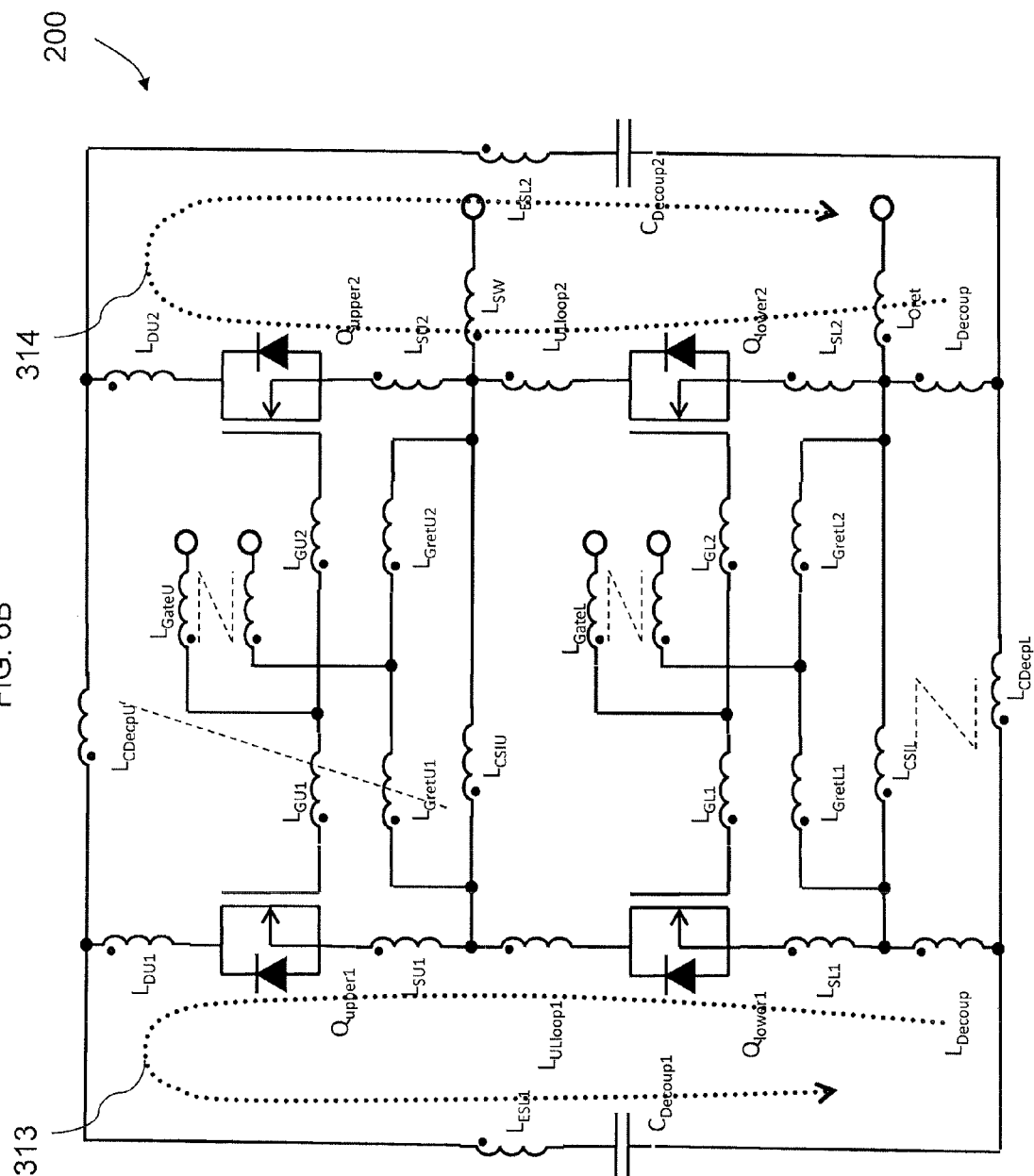


FIG. 6C

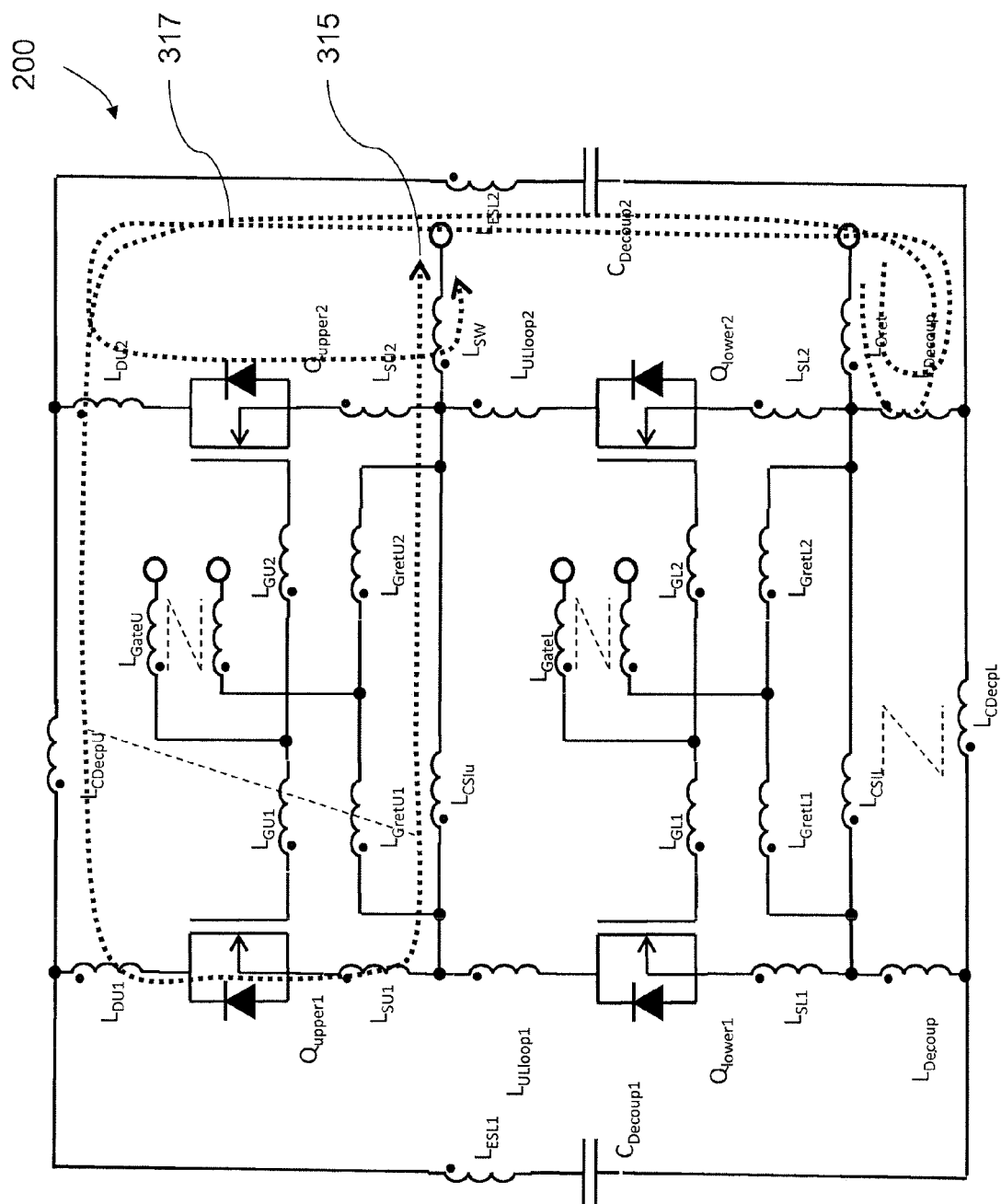


FIG. 6D

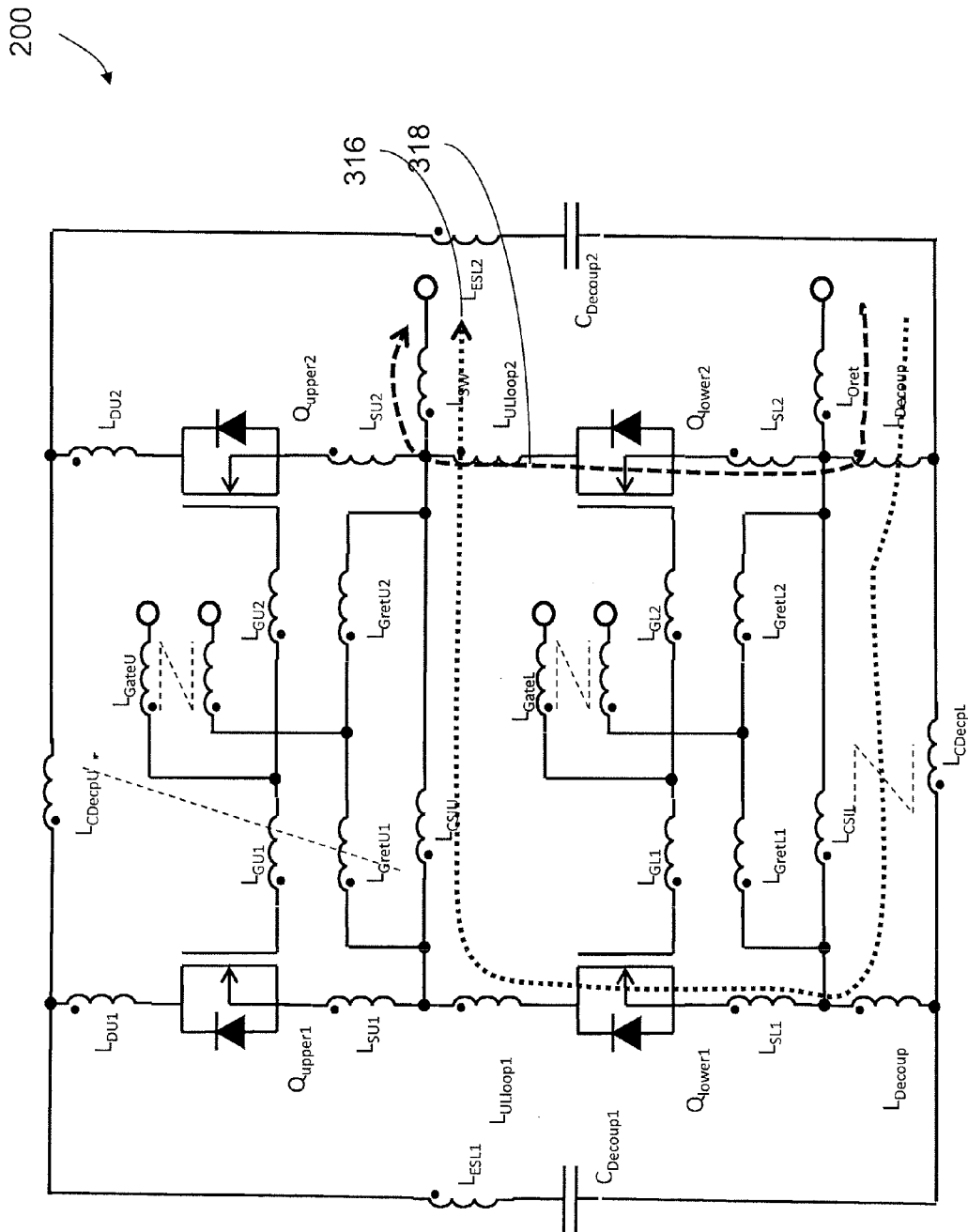


FIG. 7

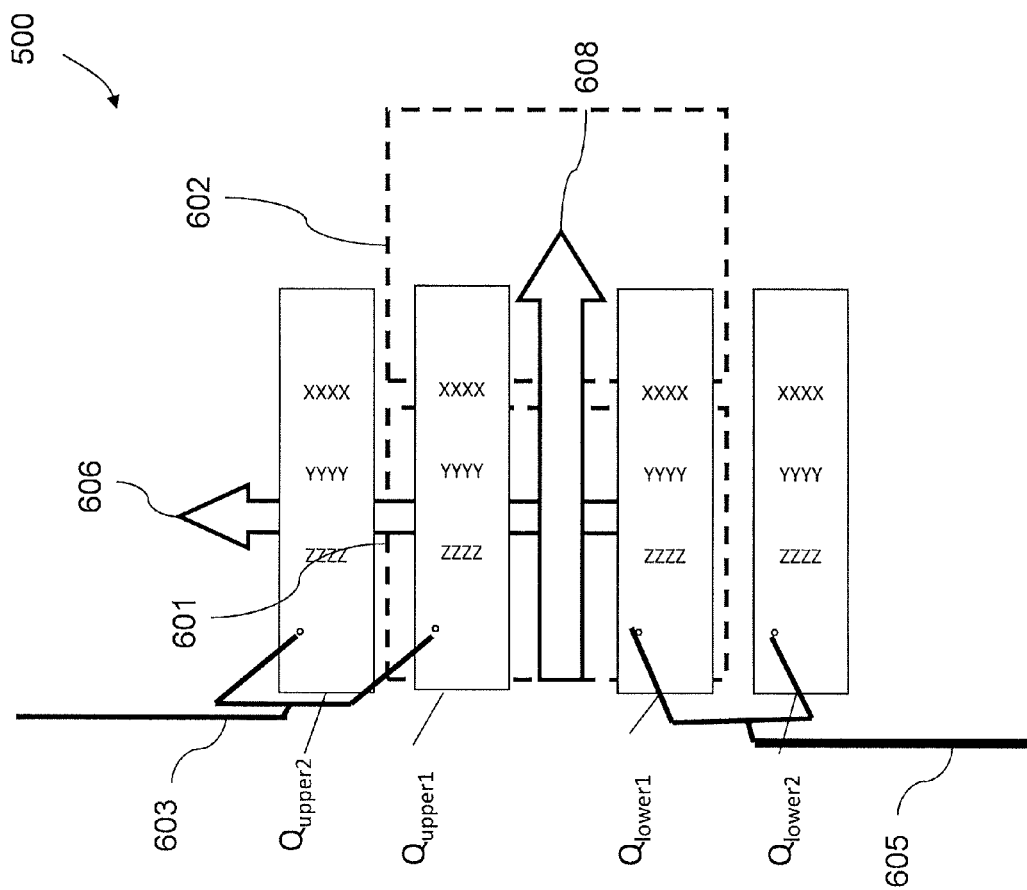


FIG. 8A

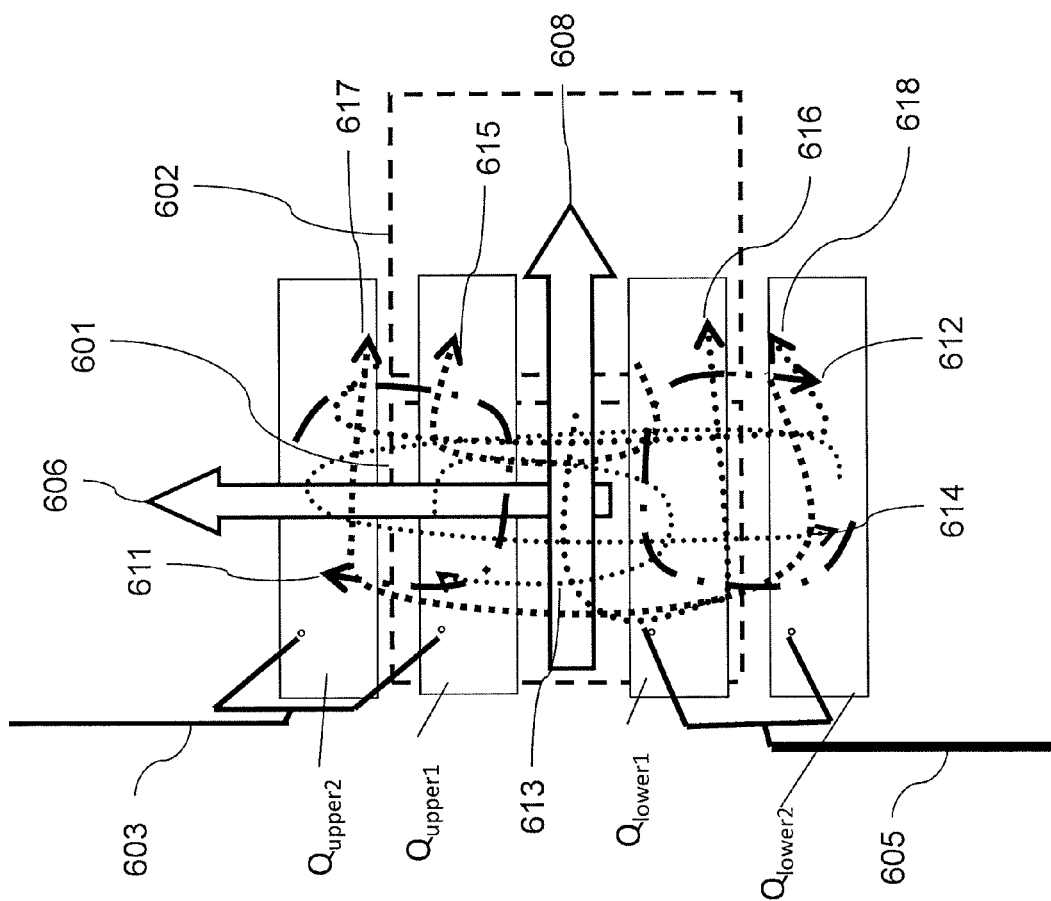


FIG. 8B

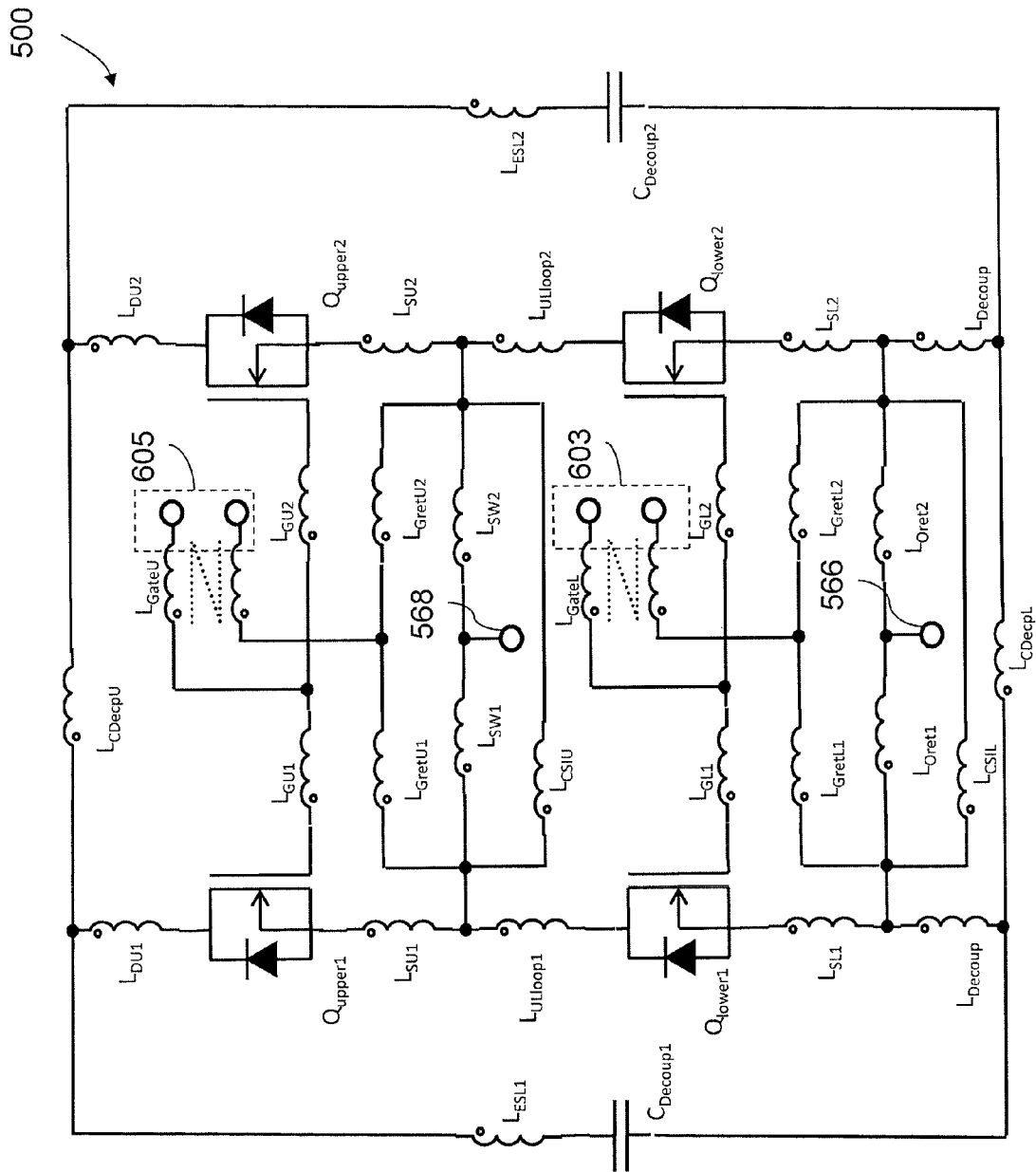




FIG. 9A

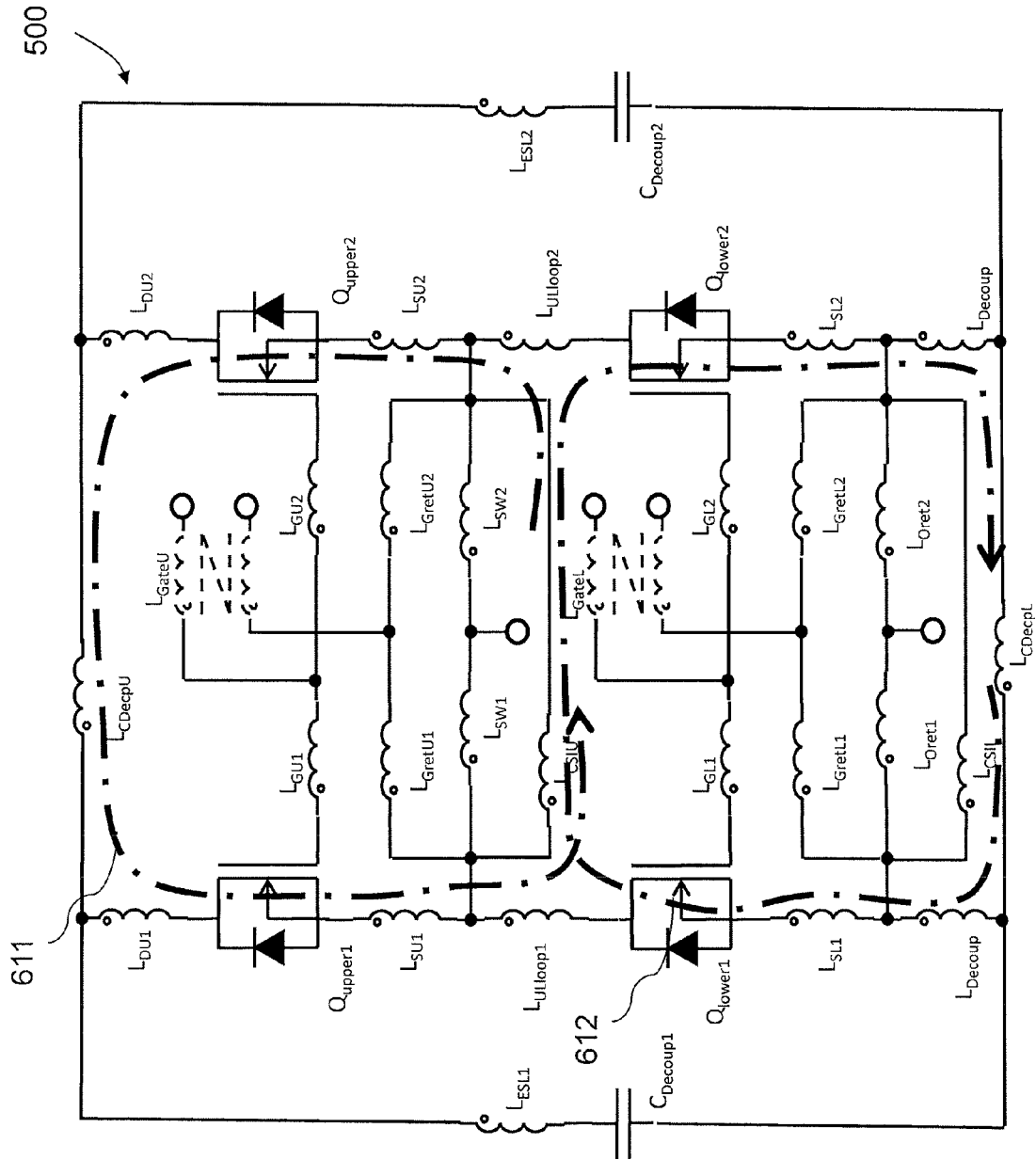


FIG. 9B

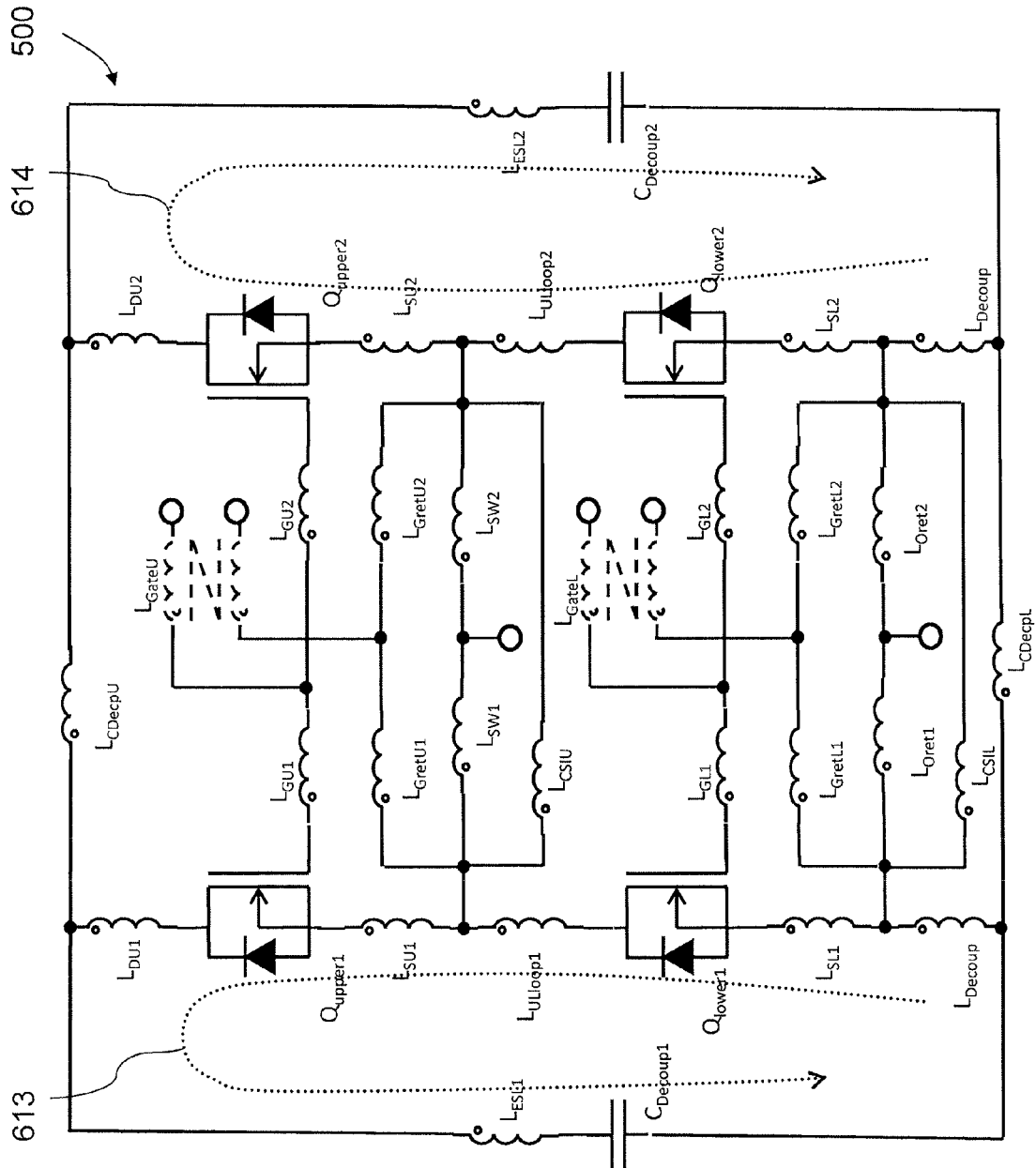


FIG. 9C

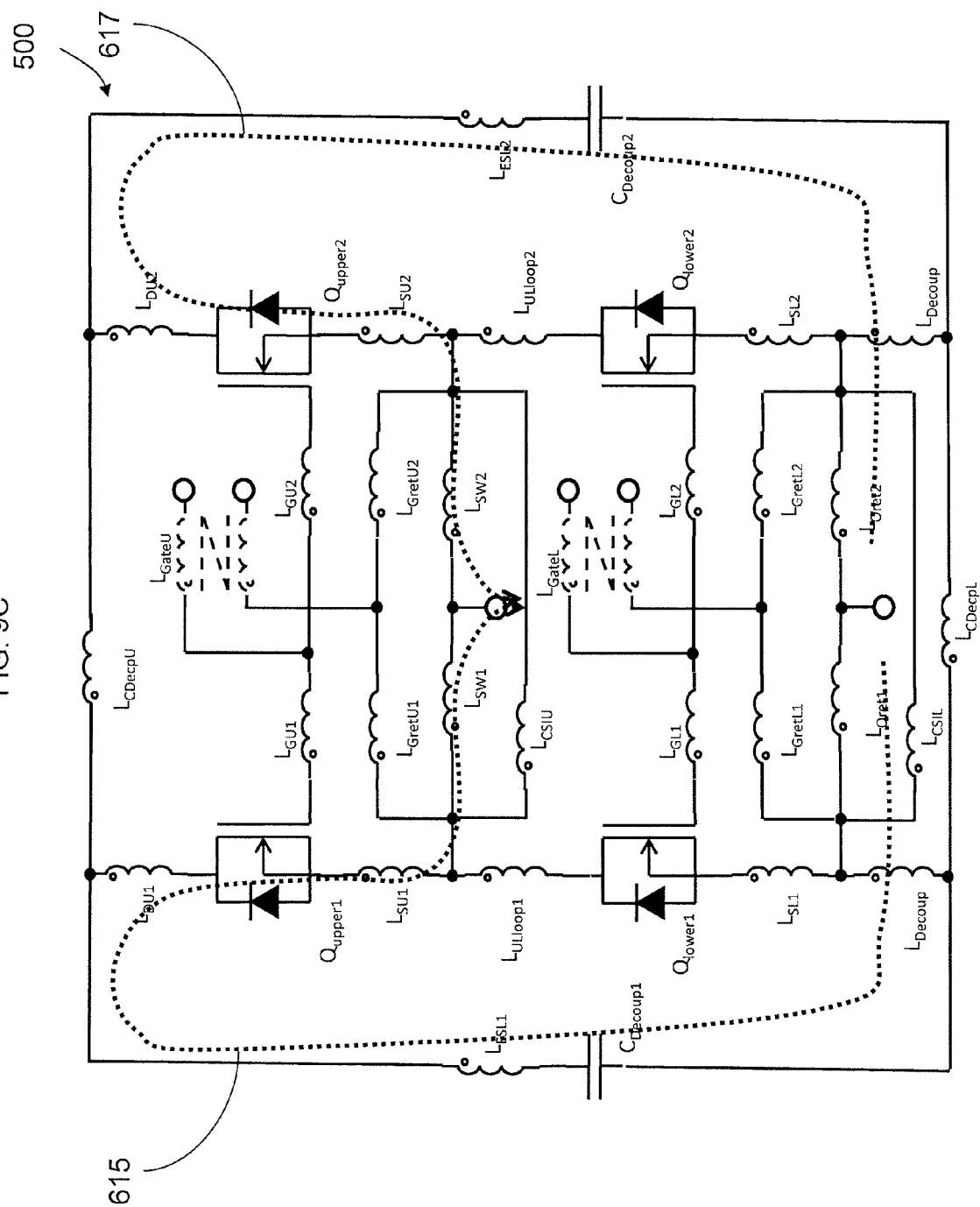


FIG. 9D

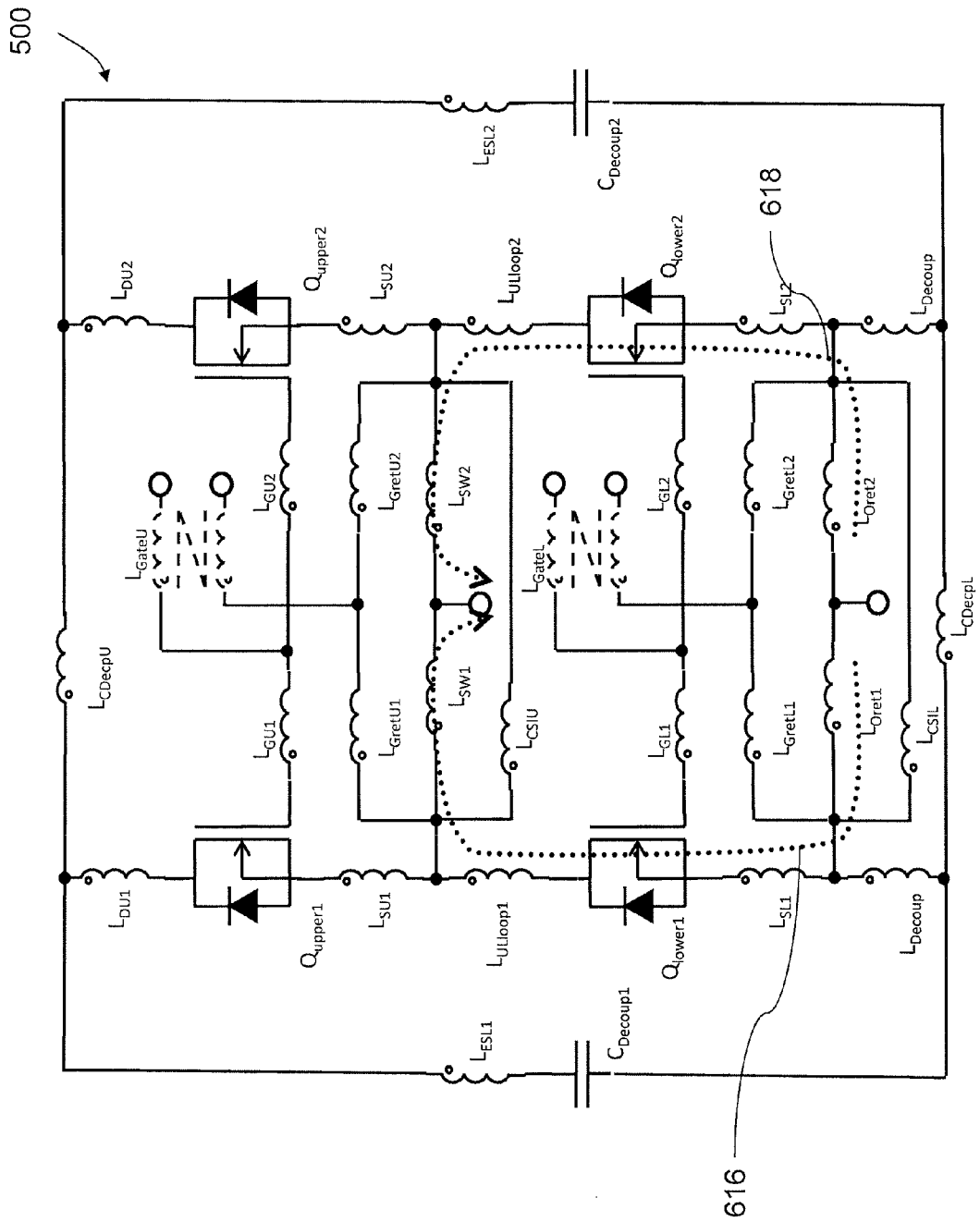


FIG. 10A

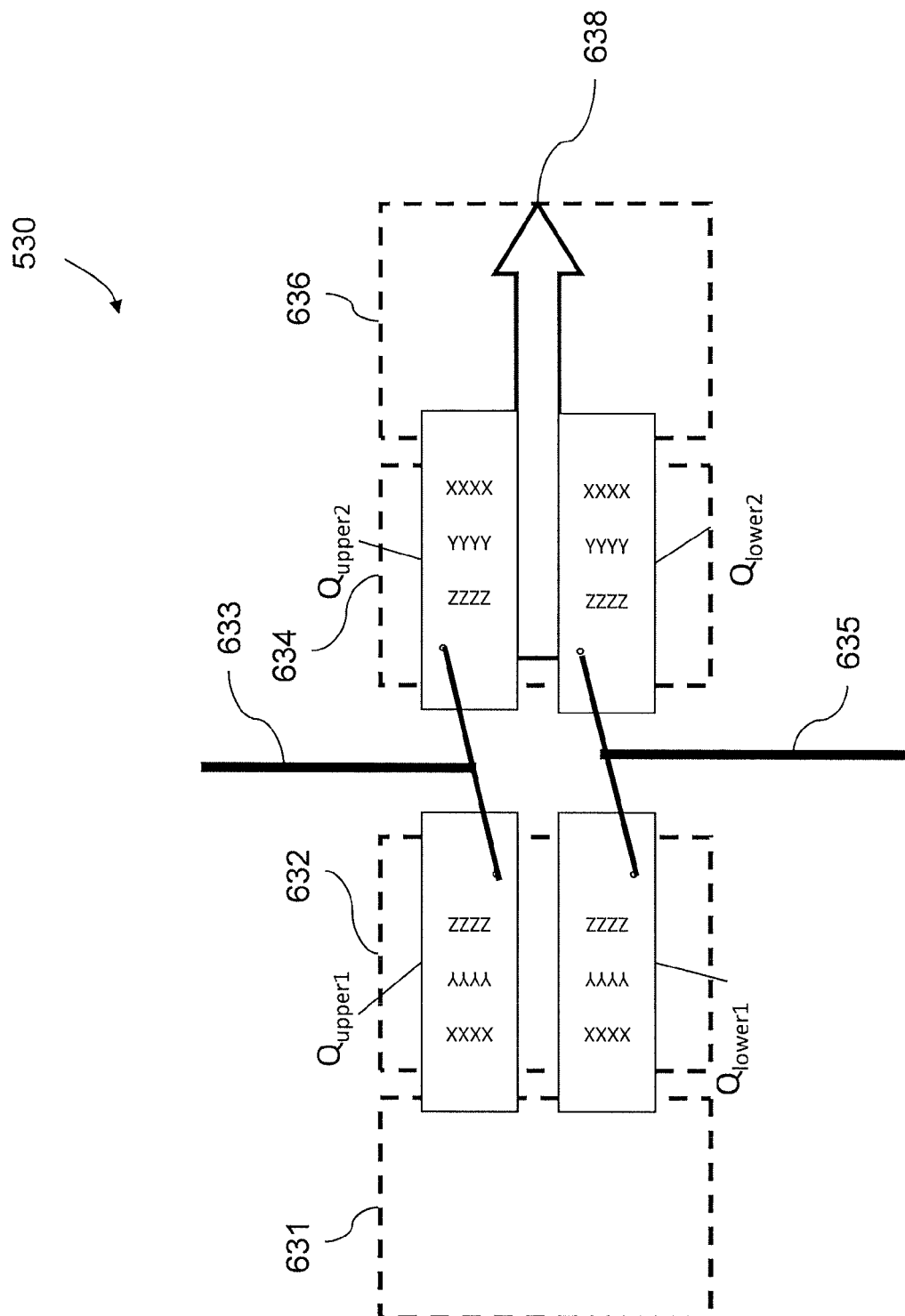


FIG. 10B

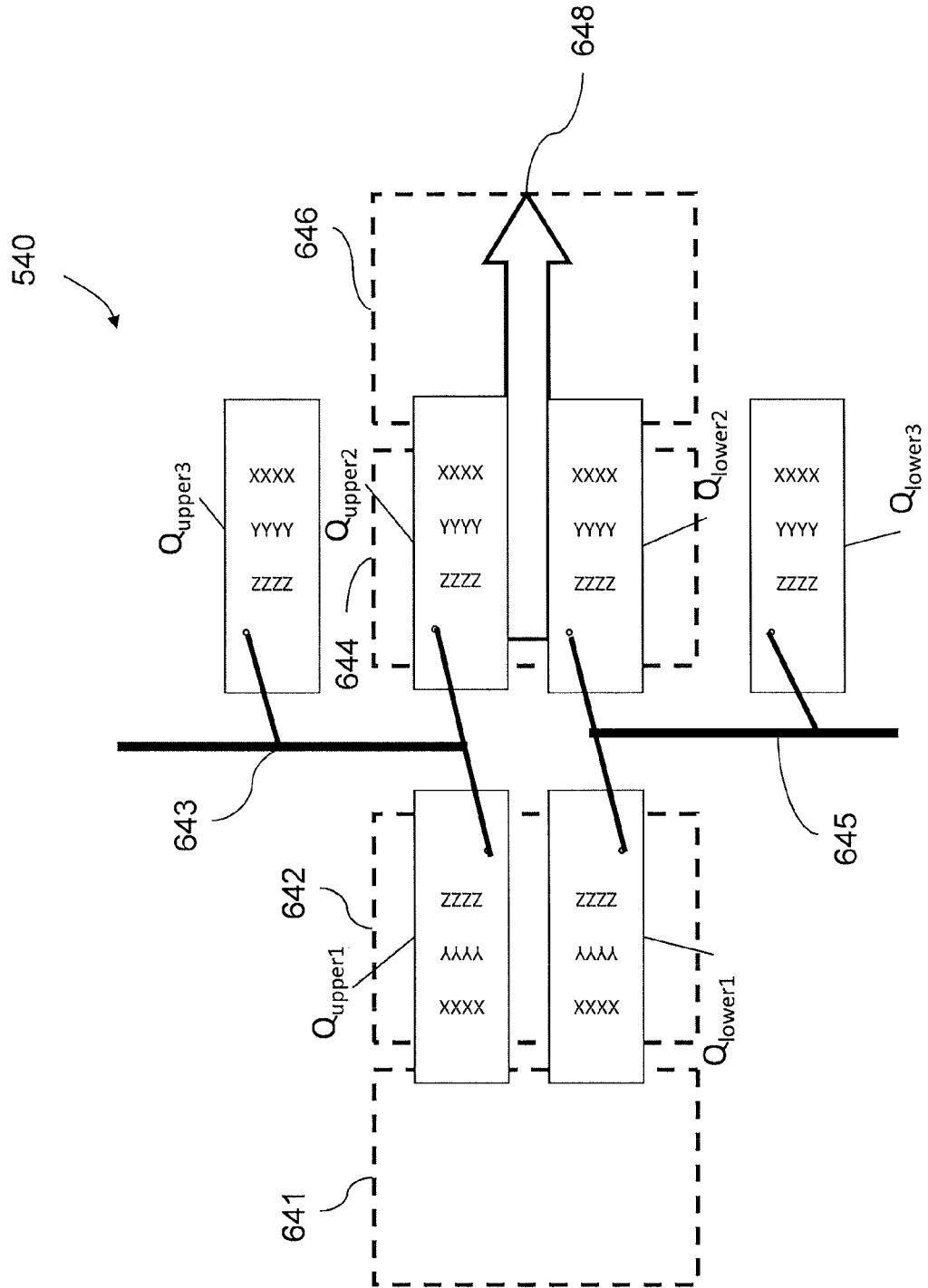
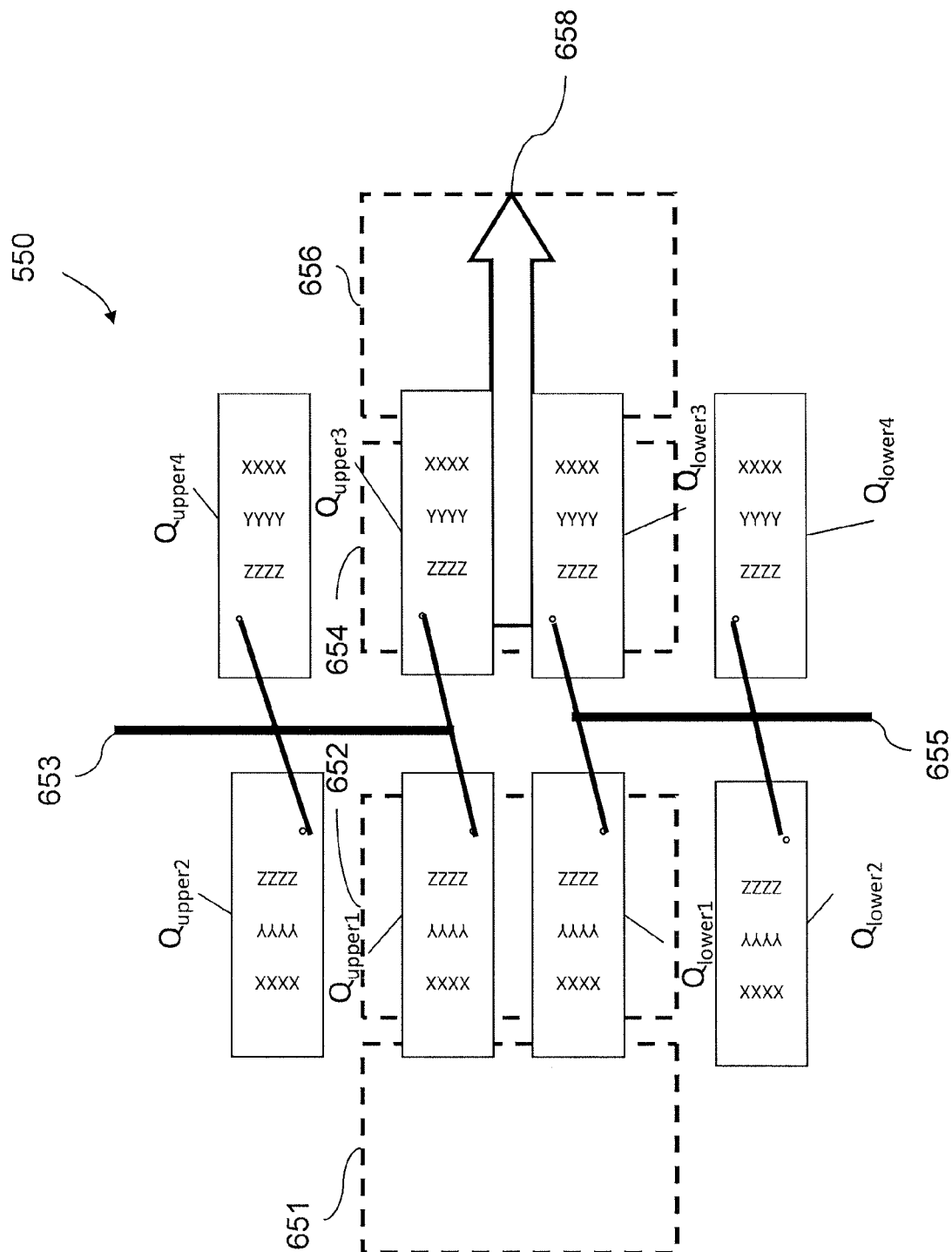


FIG. 10C



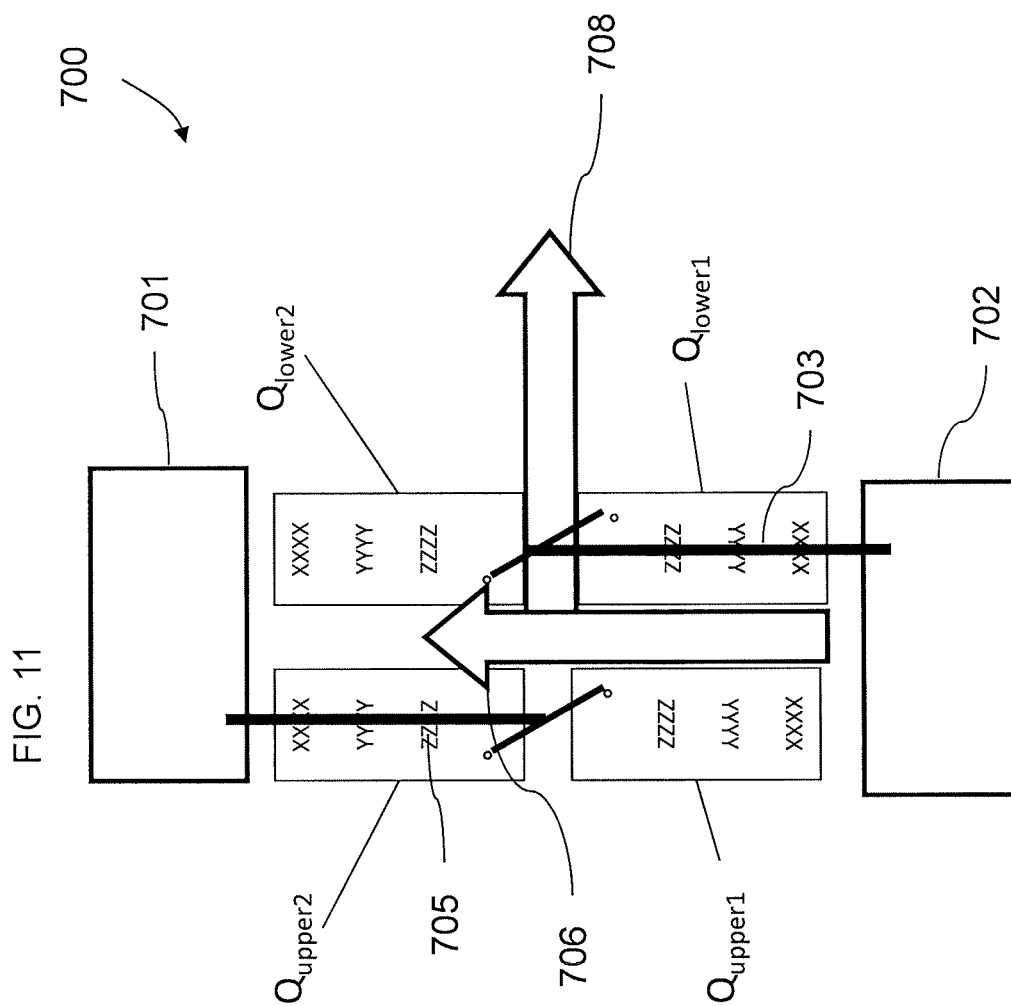
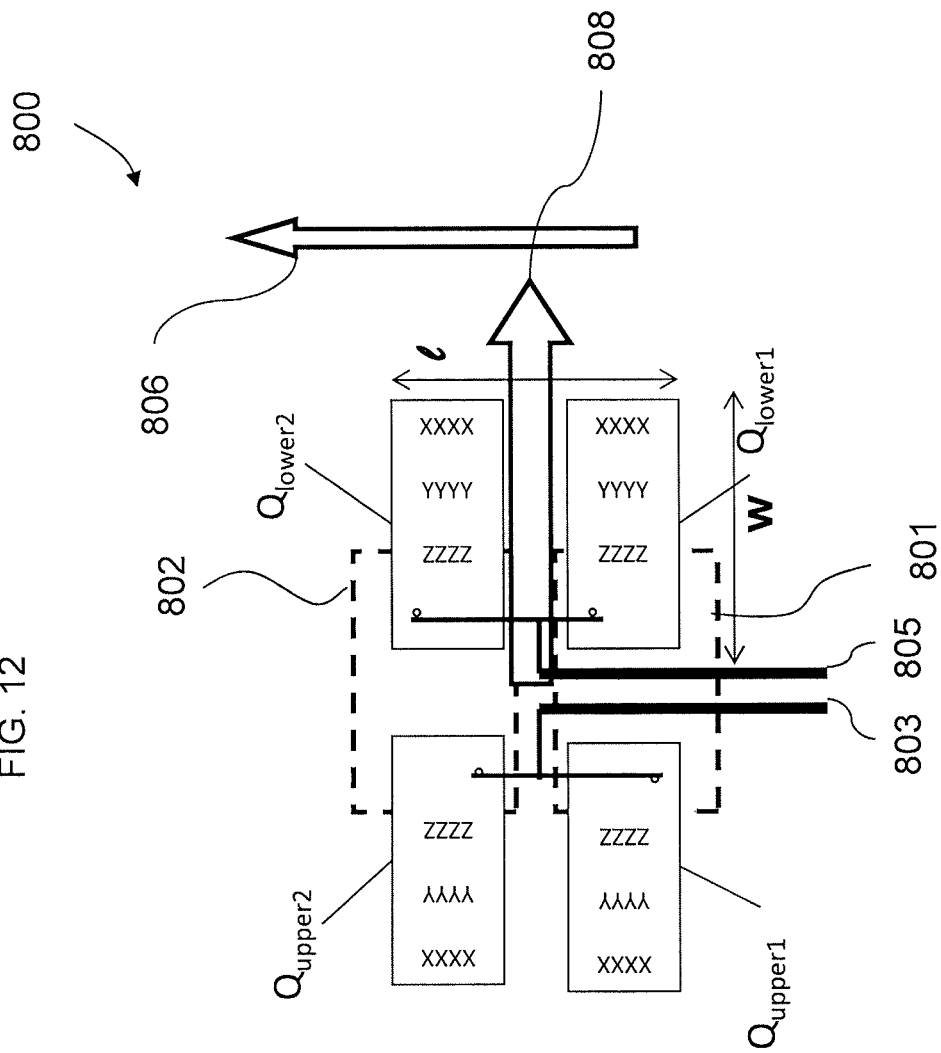




FIG. 12



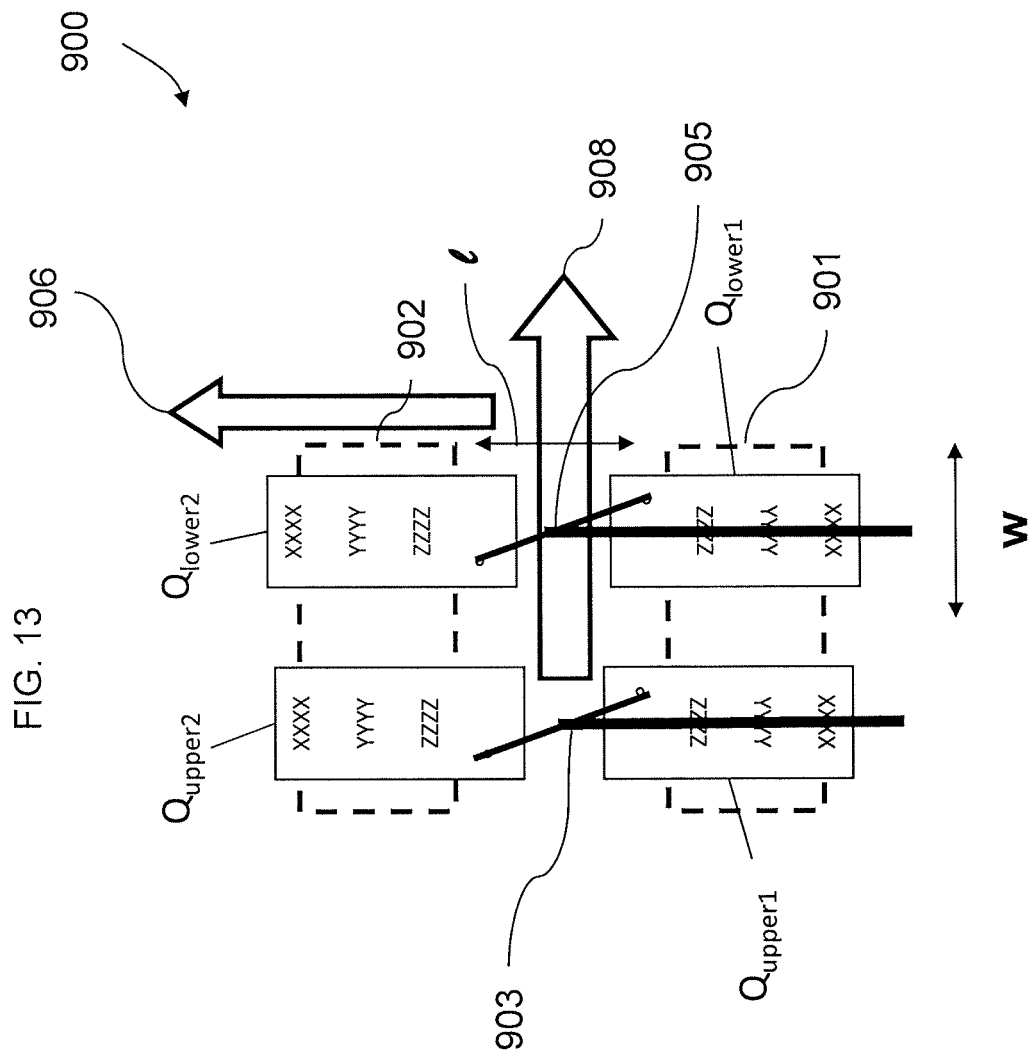




FIG. 15A

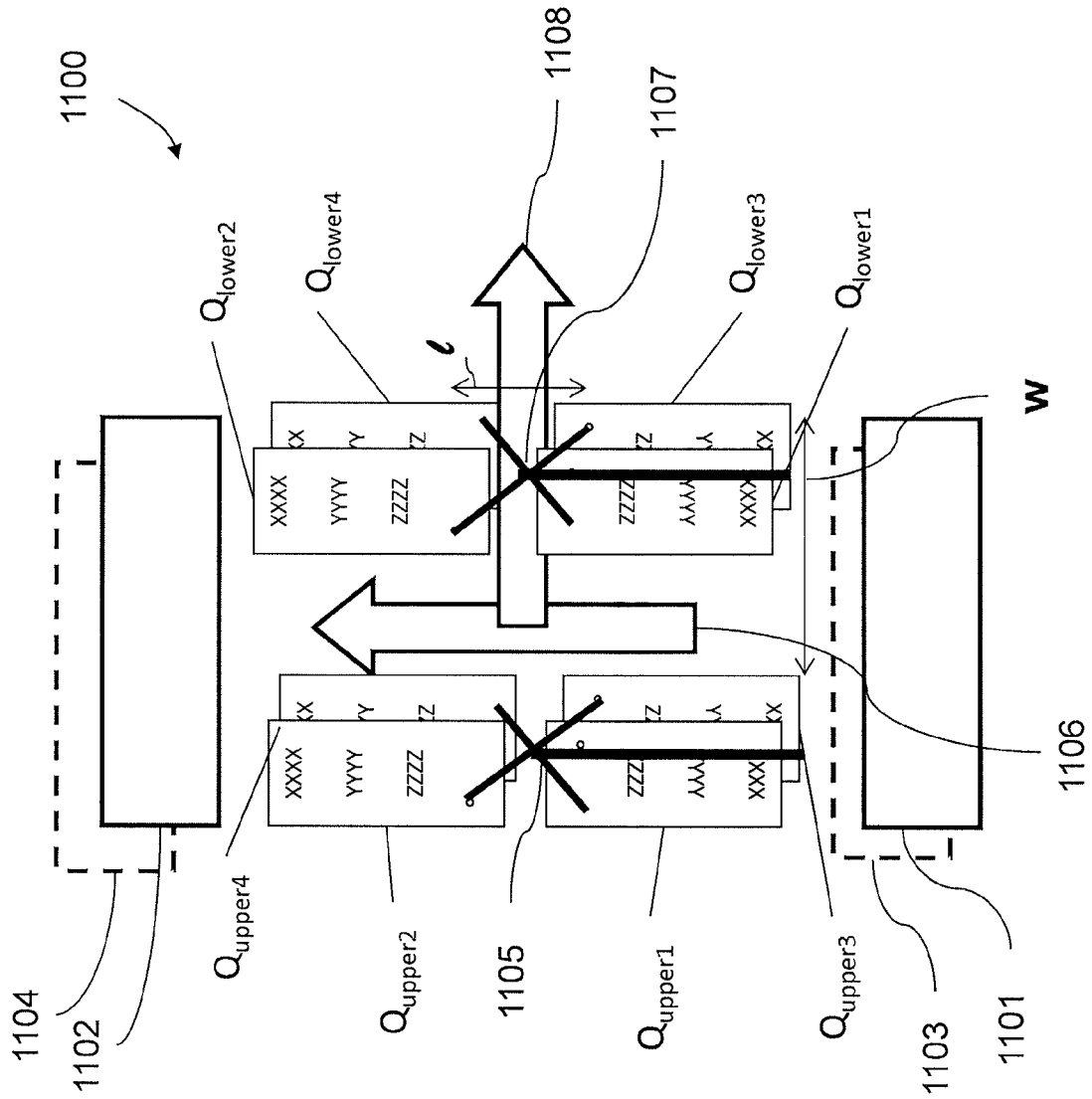
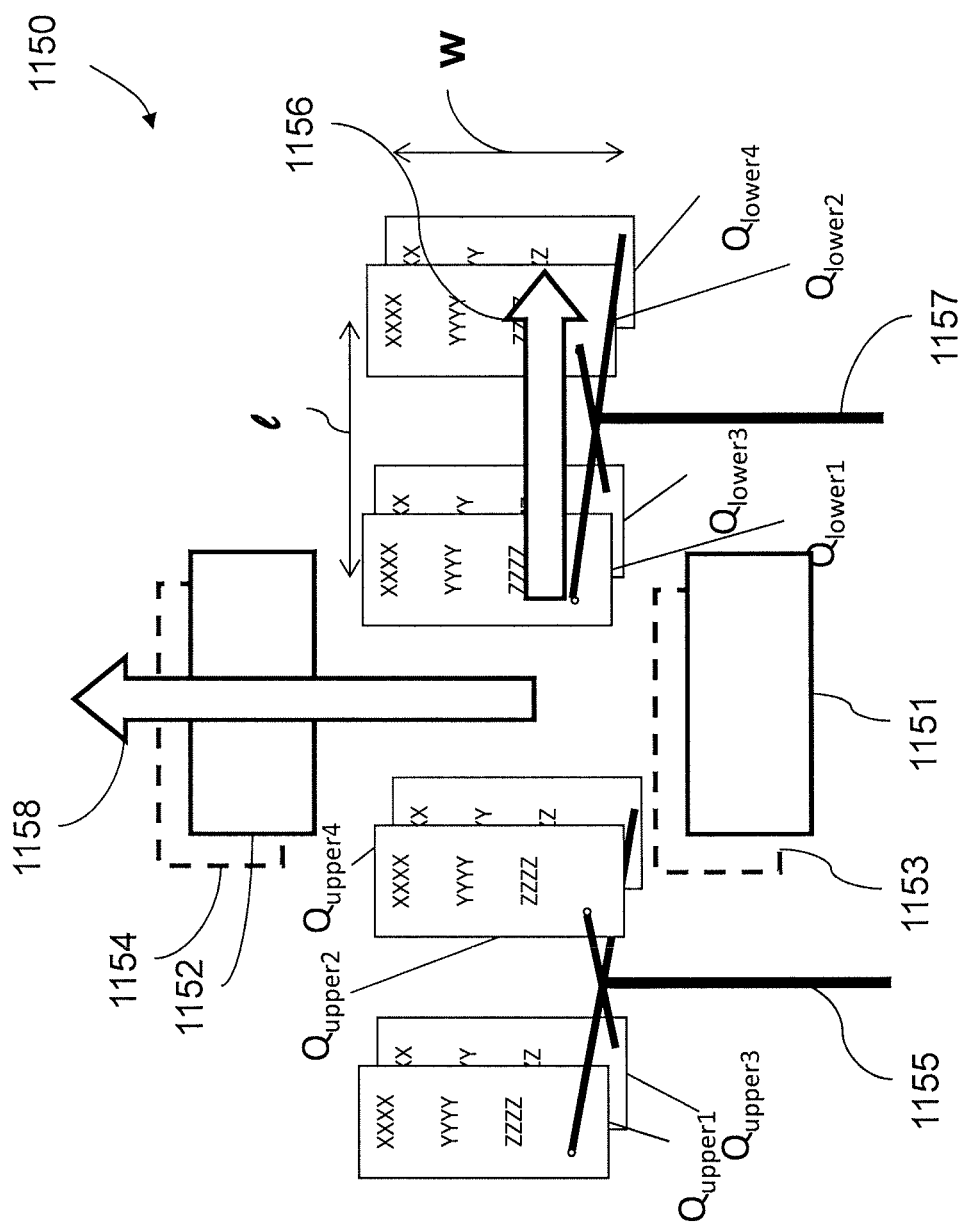


FIG. 15B



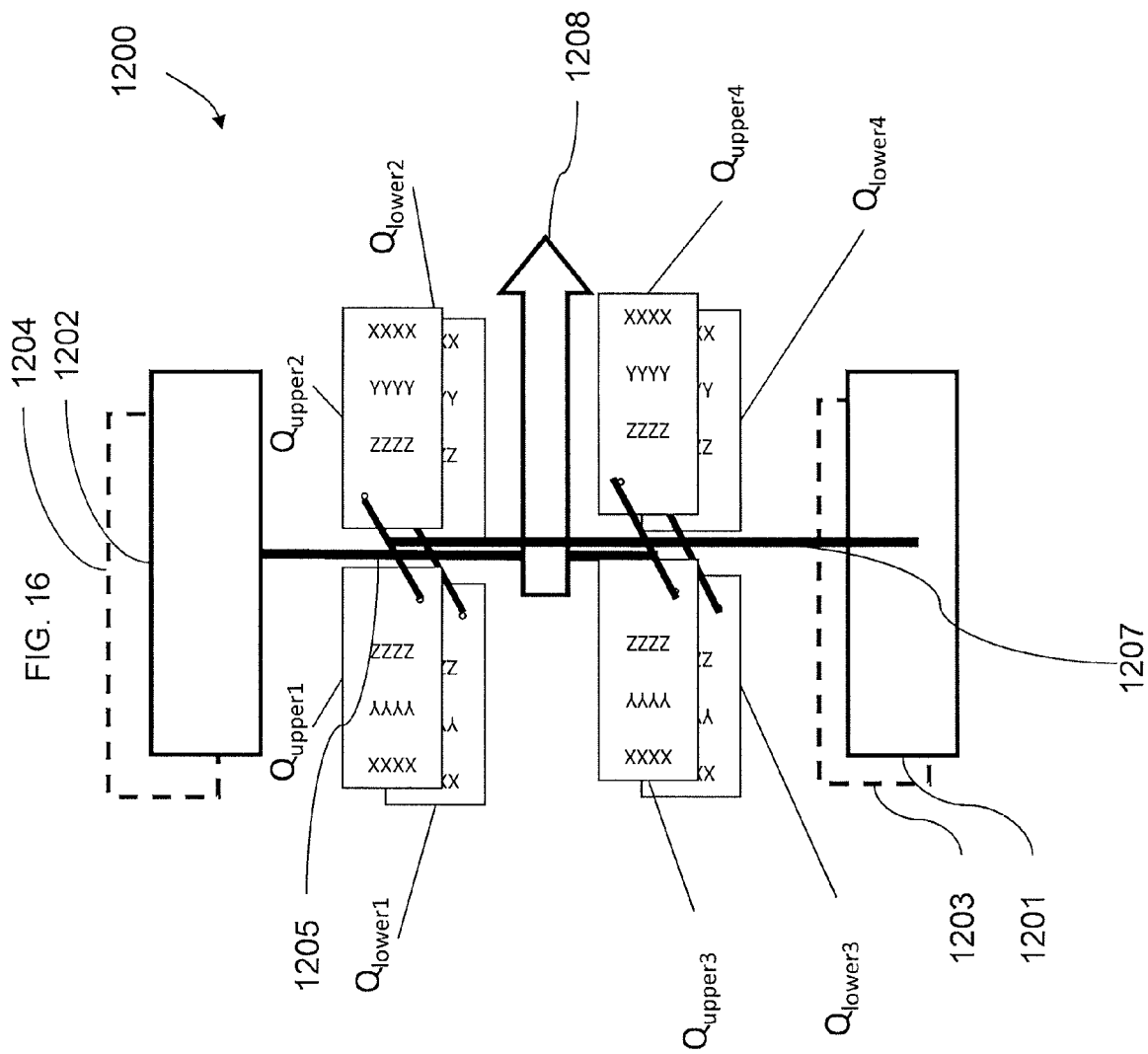
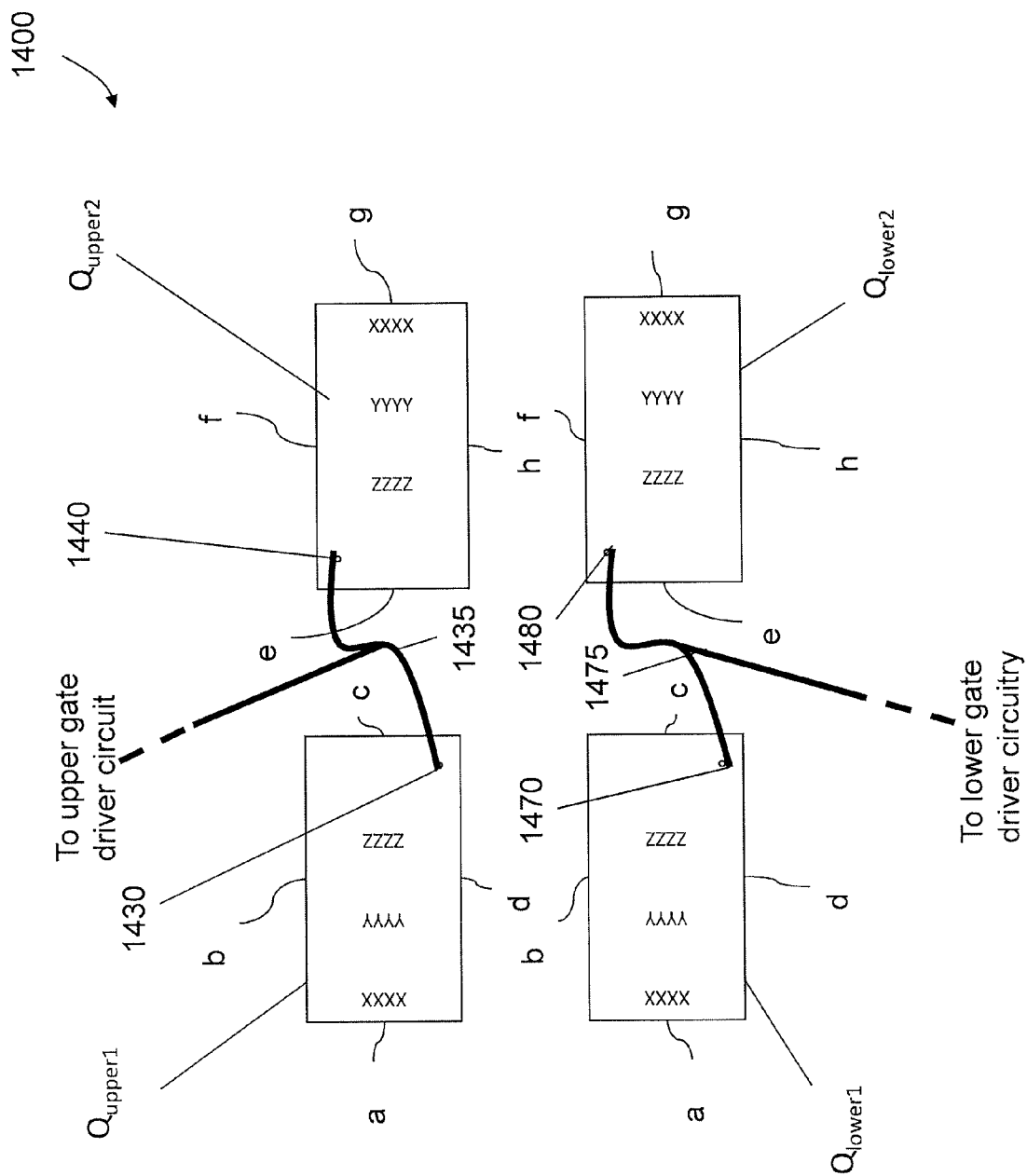




FIG. 18A





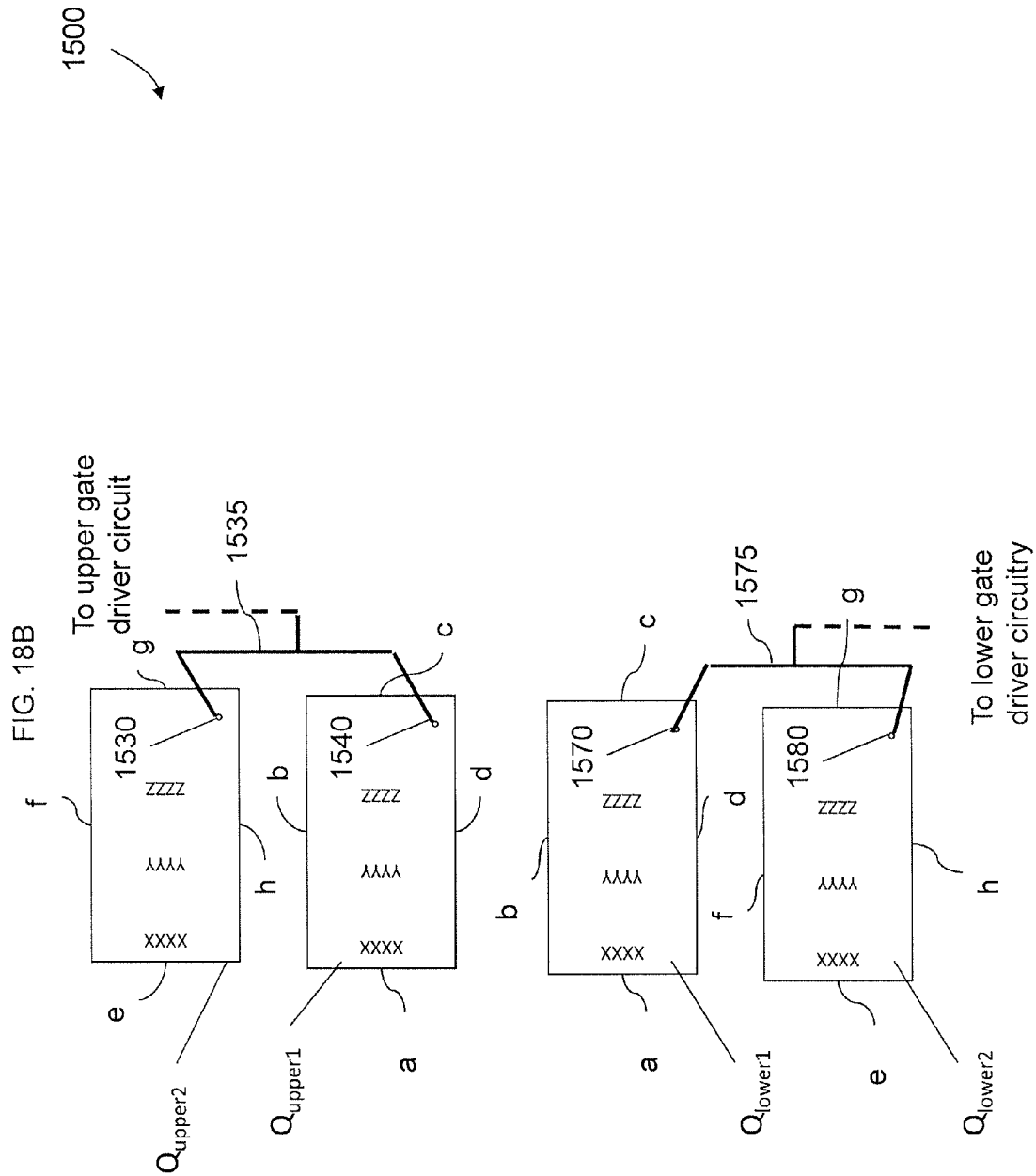
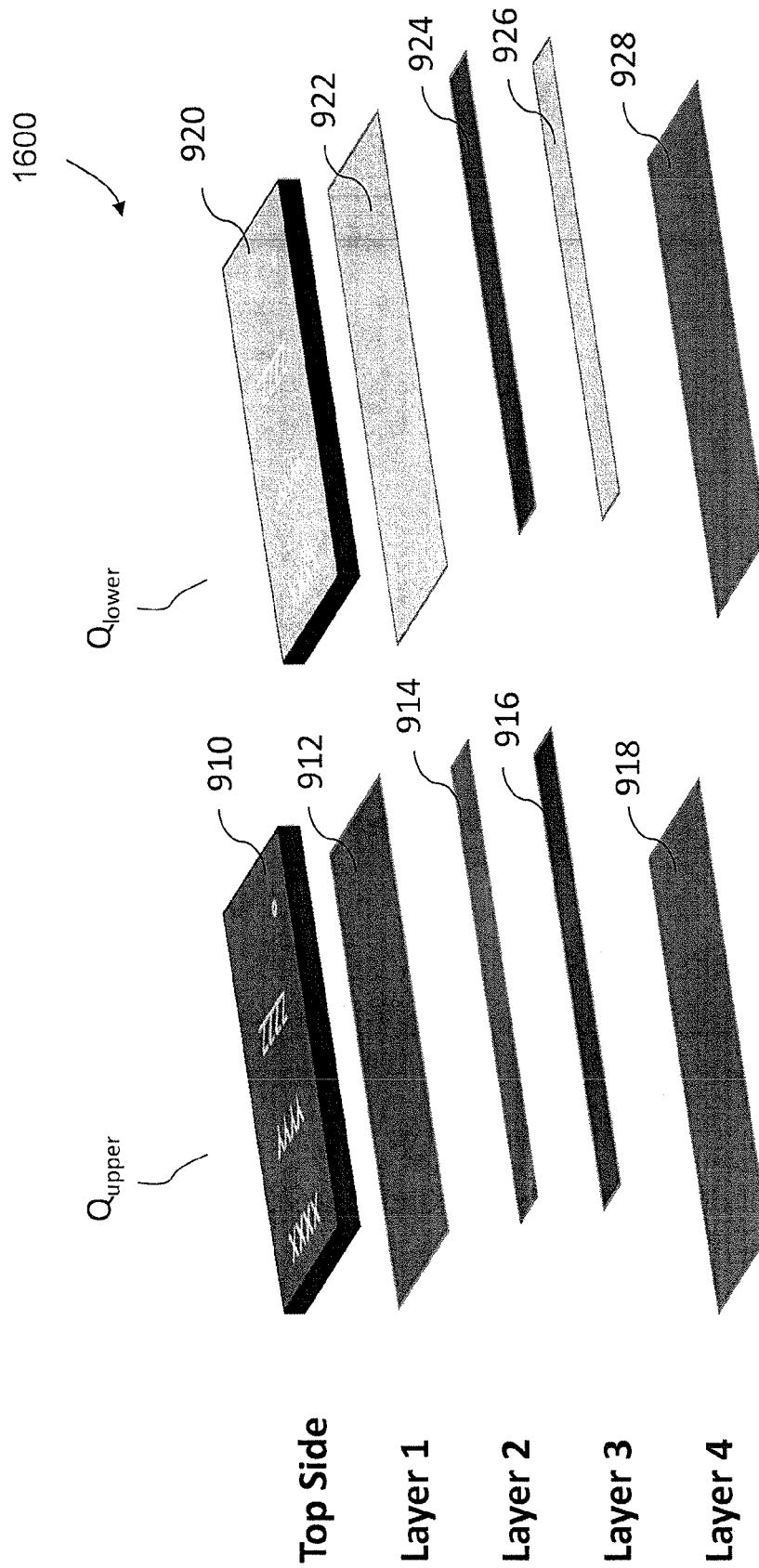


FIG. 19



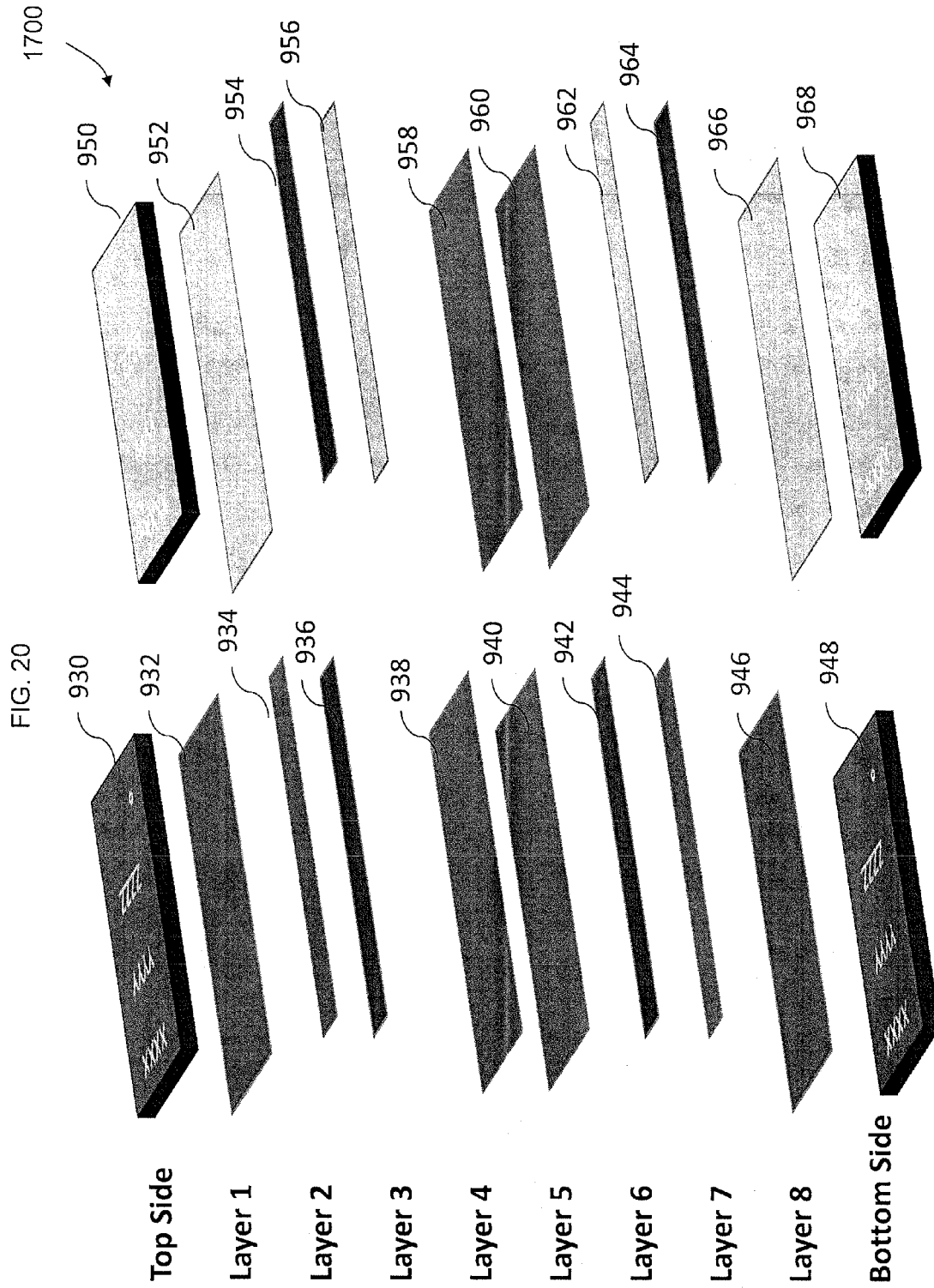
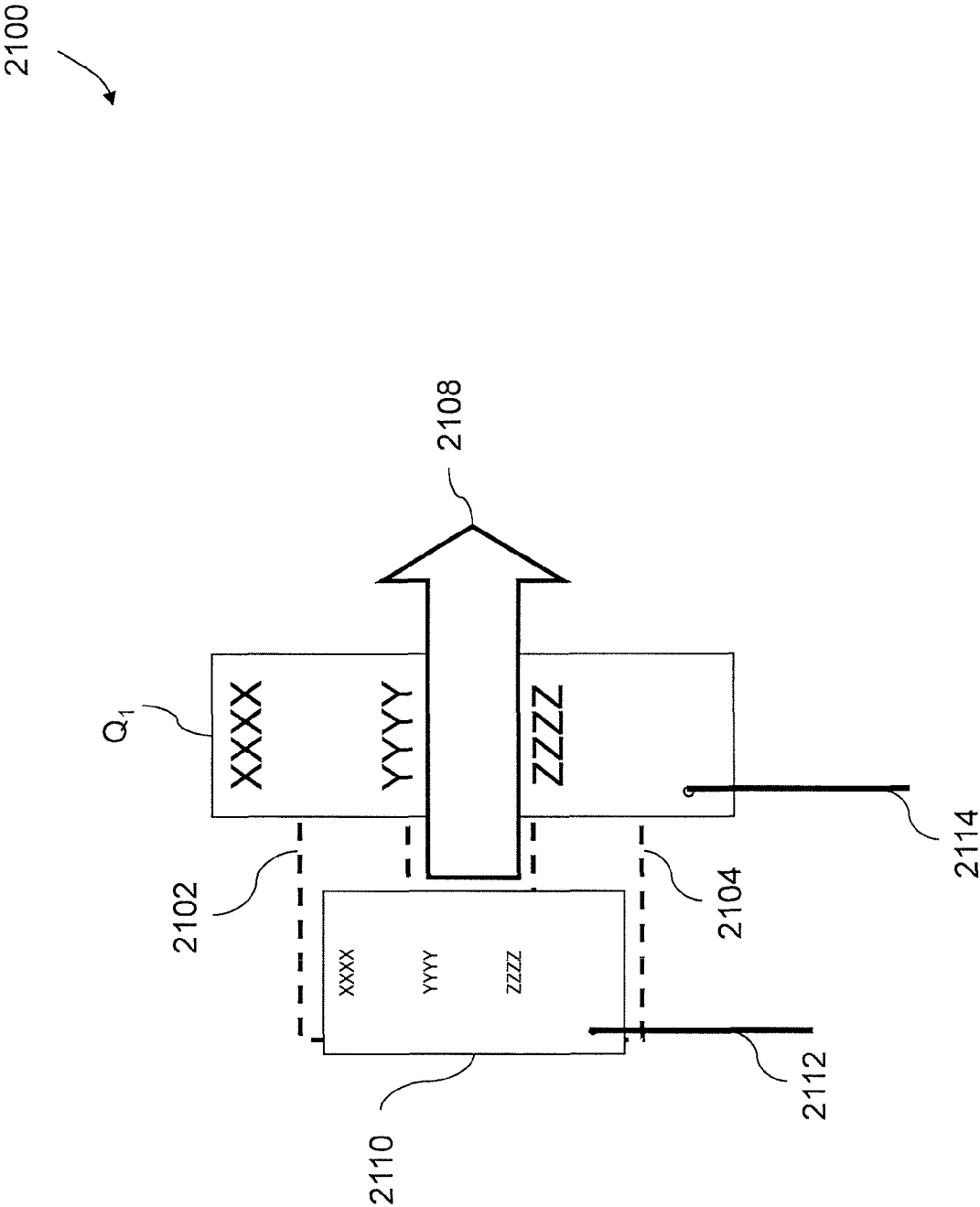


FIG. 21



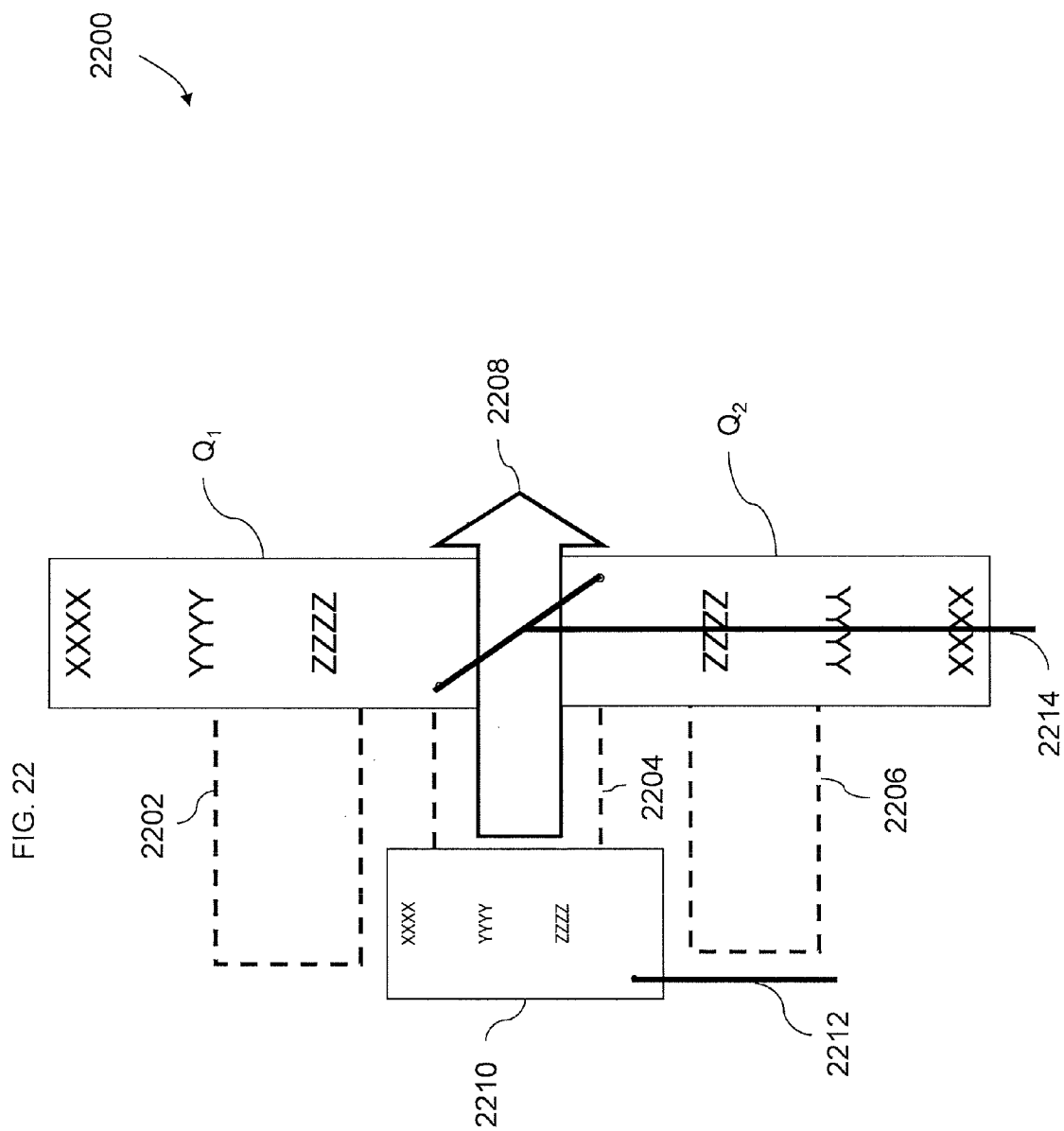
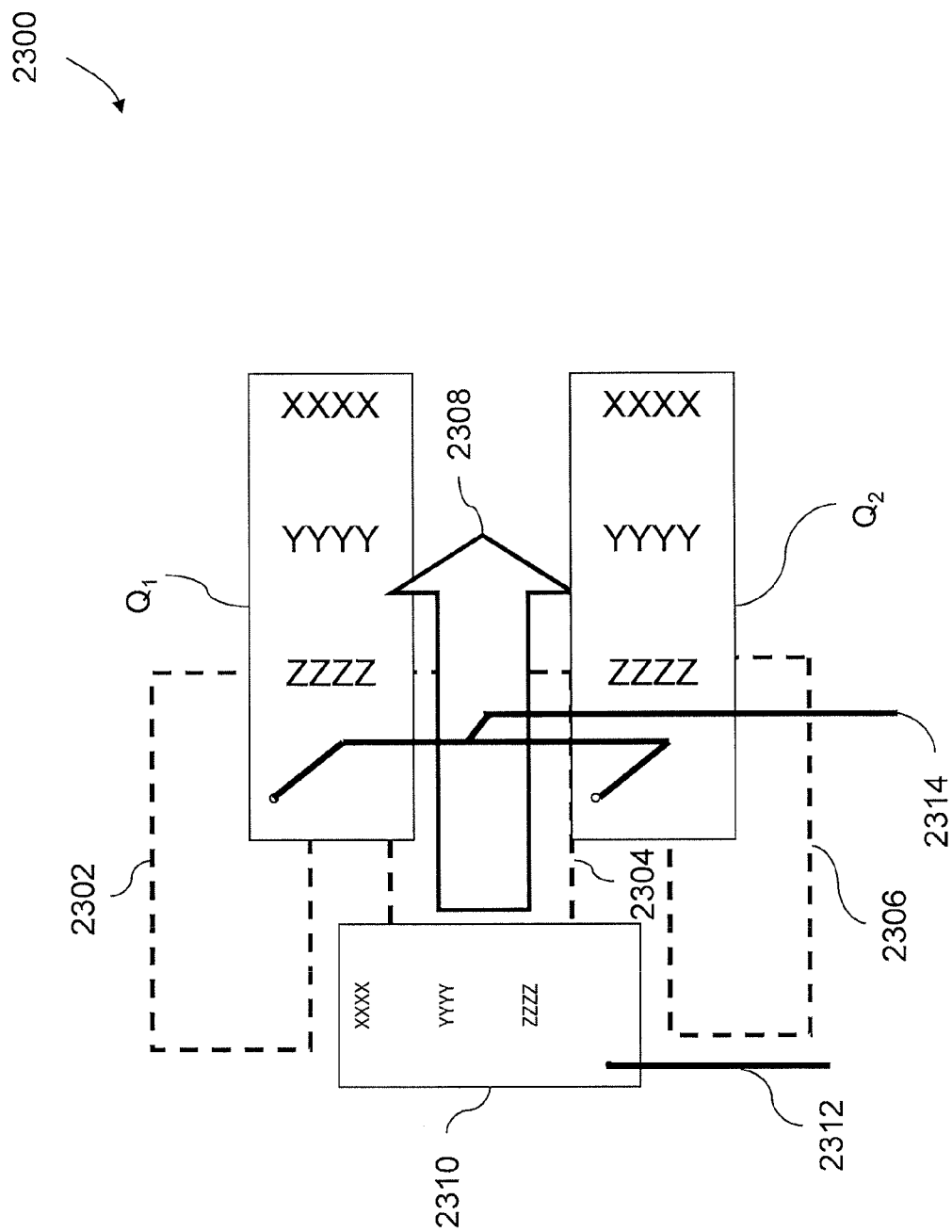


FIG. 23



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## PARALLEL CONNECTION METHODS FOR HIGH PERFORMANCE TRANSISTORS

### PRIORITY

This application claims the benefit of U.S. Provisional Patent Application No. 61/528,358, filed Aug. 29, 2011, which is incorporated by reference in its entirety.

### FIELD OF TECHNOLOGY

The described embodiments relate to the field of transistor devices, such as gallium nitride transistor devices.

### BACKGROUND

Semiconductor devices, such as field effect transistor (FET)-type semiconductor devices (e.g., metal-oxide semiconductor FETs (MOSFETs), junction-gate semiconductor FETs (JFETs), etc.), as well as bipolar junction transistor (BJT) and insulated-gate bipolar transistor (IGBT) devices use the conductive properties of semiconductor materials. Such semiconductor materials may include, for example, silicon (Si) or silicon-containing materials, graphene, germanium (Ge), gallium arsenide (GaAs), or gallium nitride (GaN).

In particular, GaN FET semiconductor devices are increasingly desirable for power semiconductor devices because of their ability to be switched up to ten times faster than commercial MOSFETs, as well as carry large current and support high voltages. Development of these devices has generally been aimed at high power/high frequency applications. Devices fabricated for these types of applications are based on general device structures that exhibit high electron mobility and are referred to variously as heterojunction field effect transistors (HFET), high electron mobility transistors (HEMT), or modulation doped field effect transistors (MODFET). These types of devices can typically withstand high voltages while operating at high frequencies.

One example of a GaN FET device is a GaN HEMT device, which may include a nitride semiconductor with at least two nitride layers. Different materials formed on the semiconductor or on a buffer layer causes the layers to have different band gaps. The different material in the adjacent nitride layers also causes polarization, which contributes to a conductive two dimensional electron gas (2DEG) region near the junction of the two layers, specifically in the layer with the narrower band gap.

In a GaN semiconductor device, the nitride layers that cause polarization typically include a barrier layer of AlGaN adjacent to a layer of GaN to include the 2DEG, which allows charge to flow through the device. This barrier layer may be doped or undoped. Because of the 2DEG region existing under the gate at zero gate bias, most nitride devices are normally on, or depletion mode devices. If the 2DEG region is depleted, i.e. removed, below the gate at zero applied gate bias, the device can be an enhancement mode device. Enhancement mode devices are normally off and are desirable because of the added safety they provide. An enhancement mode device requires a positive bias applied at the gate in order to conduct current. Examples of GaN semiconductor devices can be found in commonly assigned U.S. Patent Application Publication Nos. 2010/0258912 and 2010/0258843, both of which are incorporated by reference in their entirety.

FIG. 1A illustrates a cross-sectional view of one example of an enhancement mode GaN transistor device **100**. Com-

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monly assigned U.S. Patent Application Publication No. 2010/0258843 discloses one example of a process for forming such a device. In FIG. 1, device **100** includes substrate **101**, which may be either sapphire, SiC, or silicon, transition layers **102**, un-doped GaN material **103**, un-doped AlGaN barrier material **104**, drain ohmic contact metal **110**, source ohmic contact metal **111**, a doped p-type AlGaN or p-type GaN layer formed into a doped epitaxial gate **113**, and gate metal **112** formed over the doped epitaxial gate **113**. A layer of dielectric material **105**, such as silicon nitride, covers the barrier material **104**, such that a portion **114** of the dielectric material covers gate **113**.

FIG. 1B illustrates a top-down view of the transistor device **100**, including the location of the gate metal **112**. The lettering of transistor device **100** in FIG. 1B is used throughout this description to illustrate the orientation of respective transistor devices. For example, in transistor device **100**, source ohmic contact metal **111** may be located on one side (e.g., a right side) of transistor device **100**, while drain ohmic contact metal **110** may be located on the other side (e.g., a left side) of transistor device **100**.

Transistor devices are often used in devices requiring high current capability and fast switching capability, such as RF amplifiers, switching converters, or other circuits. A well known technique for increasing current-handling capabilities of devices is to use multiple transistor devices connected in parallel. Paralleling of transistor devices increases their current capability, thereby increasing the power throughput of the circuit. Paralleling of transistor devices is also frequently used to distribute heat loss in devices.

Examples of paralleled transistors are described, for example, in U.S. Pat. No. 7,330,046, entitled "Circuits and Methods for Failure Prediction of Parallel MOSFETs," and, for example, in J. Forsythe, International Rectifier, "Paralleling of Power MOSFETs for higher Power Output," which are hereby incorporated by reference in their entirety. Examples of RF applications of paralleled transistors are described, for example, in H. Granberg, Motorola Inc. Engineering Bulletin EB 104, "GET 600 WATTS RF FROM FOUR POWER FETs" (1983), and R. Frey, Microsemi Power Products Group Application Note 1814, "Paralleling MOSFETs in RF Amplifiers" (2010), which are hereby incorporated by reference in their entirety.

One common application for paralleled transistor devices is a switching device including a paralleled group of transistors (e.g., GaN transistors) configured to act as a single transistor. The paralleled transistors may include a single gate driver for the switching device.

FIG. 2 illustrates one example of a conventional design layout for a paralleled switching circuit **120**. Circuit **120** includes four pairs of parallel transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{upper3}$ ,  $Q_{upper4}$ ,  $Q_{lower1}$ ,  $Q_{lower2}$ ,  $Q_{lower3}$ ,  $Q_{lower4}$ , each of which may be, for example, GaN FET transistor devices, MOSFET transistor devices, or other transistor devices known in the art. The parallel transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{upper3}$ ,  $Q_{upper4}$ ,  $Q_{lower1}$ ,  $Q_{lower2}$ ,  $Q_{lower3}$ ,  $Q_{lower4}$ , are formed on a single side of a printed circuit board (PCB). Upper parallel transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{upper3}$ , and  $Q_{upper4}$  are driven by a common gate transfer control line **212**, and lower parallel transistor devices  $Q_{lower1}$ ,  $Q_{lower2}$ ,  $Q_{lower3}$ ,  $Q_{lower4}$  are driven by a common gate transfer control line **214**. Each set of upper and lower transistors in circuit **120** includes one or more respective decoupling capacitors **202**, **204**, **206**, **208**. A switch node current **216** of circuit **120** (i.e., an output current) exits circuit **120** in a lengthwise direction.

In the design of a paralleled switching circuit, or any other circuit including paralleled transistor devices, however,

numerous factors must be accounted for to realize an efficient and reliable circuit. In particular, different types of transistor devices have different requirements and design considerations for implementation in parallel circuits. For example, when paralleling GaN FETs, the characteristics of the GaN transistors to be used must be considered. Most notably, the selection of devices, such as whether to use more small devices or fewer large devices to achieve the desired circuit parameters, whether the selected devices have positive or negative temperatures coefficients for certain key characteristics, such as threshold voltage  $V_{th}$  and drain-source resistance  $R_{DSon}$ , and whether part-to-part and/or lot-to-lot variations may affect the overall design.

Another consideration for designing transistor devices, and in particular GaN FET semiconductor devices, is the layout of the circuit. Layout designs should take into account various factors including printed circuit board (PCB) restrictions (including board populating) and placement and routing design. In addition, GaN semiconductor devices require additional considerations due to their small size, compact connection structure, and high demand on specifications such as current and voltage.

Another area that must be considered is the parameters of the circuits themselves. Circuits employing FET devices typically require certain circuit changes to ensure maximum performance from each of the devices, and to ensure that the paralleled switch can function at near theoretical maximum performance.

For example, one parameter that must be controlled is the Miller capacitances in the circuit. The Miller capacitance represents the increased equivalent input capacitance in an amplifier due to amplification of capacitance between the input and output terminals of the amplifier. In a transistor, Miller capacitance is driven by the rate of change over time of the voltage (dv/dt) of the transistor. Miller capacitance can induce a current into the gate path during switching events.

As another example, because GaN transistor devices are designed to have increased switching frequency and improved packaging, they are particularly sensitive to common source inductance (CSI). CSI is a parasitic inductance at a common source node, which can generate a voltage that is shared by the drain-to-source current path and the gate driver loop of a transistor device. In a transistor, CSI is dependent upon the rate of change over time of the current (di/dt) flowing through the transistor. CSI can induce unwanted gate voltages into a transistor device. Common source inductance between paralleled transistors is described, for example, in A. Elbanhawey, Fairchild Semiconductor Application Note AN-7019, "Limiting Cross-Conduction Current in Synchronous Buck Converter Designs" (Rev. A. 2005), which is hereby incorporated by reference in its entirety.

FIG. 3 illustrates the effect of CSI in a circuit 150 including a pair of parallel transistor devices  $Q_1$ ,  $Q_2$ , which may be, for example, GaN FET transistor devices, connected in parallel. A first transistor device  $Q_1$  includes parasitic capacitances including drain-to-source capacitance  $C_{ds1}$ , gate-to-drain capacitance  $C_{gd1}$ , and gate-to-source capacitance  $C_{gs1}$ . A second transistor device  $Q_2$  includes parasitic capacitances including drain-to-source capacitance  $C_{ds2}$ , gate-to-drain capacitance  $C_{gd2}$ , and gate-to-source capacitance  $C_{gs2}$ . The gates of first and second transistor devices  $Q_1$ ,  $Q_2$  are electrically connected to a common voltage driver  $V_{GateDrive}$  via respective gate transfer control lines 222, 224. Each gate transfer control line 222, 224 includes a respective gate transfer control line inductance  $L_{G1}$ ,  $L_{G2}$ . First and second transistor devices  $Q_1$ ,  $Q_2$  may be, for example, low-side transis-

tors in a switching device, with their drains connected to one or more upper-side transistors  $Q_{UpperSW}$ .

First and second transistor devices  $Q_1$ ,  $Q_2$  share a common source node 216 that experiences parasitic common source inductances  $L_{CSP1}$  and  $L_{CSP2}$  connected in series with  $L_{CSG1}$  and  $L_{CSG2}$ , respectively. FIG. 3 shows one example of a gate driver loop current  $I_{dv/dt}$  that may be formed as a result of the Miller capacitances of transistor device  $Q_1$ , and a gate voltage  $V_{di/dt}$  that may be generated as a result of common source inductance  $L_{CSP1}$  of transistor device  $Q_1$ . As shown in circuit 150, the source current  $I_{L-CS}$  of first transistor device  $Q_1$  flows through the common source inductance  $L_{CSP1}$ , creating a voltage  $V_{di/dt}$  at the gate of transistor device  $Q_1$  when source current  $I_{L-CS}$  is transient. Because voltage  $V_{di/dt}$  affects the voltage on the gate driver loop of transistor devices  $Q_1$ ,  $Q_2$ , a change of source current  $I_{L-CS}$  (e.g., during transient events) may undesirably affect operation of one or both of transistor devices  $Q_1$ ,  $Q_2$ . For example, in some cases, voltage  $V_{di/dt}$  could turn transistor device  $Q_1$  and/or transistor device  $Q_2$  on and/or off unexpectedly. In other cases, voltage  $V_{di/dt}$  could potentially overload the voltage at the respective gates when transistor devices  $Q_1$ ,  $Q_2$  are turned on. Particularly for GaN devices and other semiconductor devices with high switching frequency capability and/or frequent current transients, it is desirable to maintain a low common source inductance. It is further beneficial to prevent unexpected gate turn on for  $Q_1$  during a high dv/dt event that can inject current into the gate driver loop via Miller capacitances. Keeping the common source inductance low also keeps the gate loop impedance low, thereby raising the threshold magnitude of the Miller-induced current that will corrupt the gate of the transistor.

Accordingly, there is a need and desire for a semiconductor device, circuit, layouts for such devices, and methods of forming such devices and circuits, that experience reduced negative effects from common source inductance, inter device inductance and other detrimental effects.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A shows a cross sectional view of a conventional gallium nitride (GaN) semiconductor device.

FIG. 1B shows a top-down view physical drawing of a conventional gallium nitride (GaN) semiconductor device.

FIG. 2 shows a top-down view of a design layout using GaN semiconductor devices that would be typical for most designers to parallel devices.

FIG. 3 shows a schematic view of a switching circuit including paralleled transistor devices.

FIGS. 4A and 4B show schematic views of the simplified gate loops including parasitic elements determining the immunity to change in voltage over time and change in current over time, respectively.

FIG. 5A shows a top view of a semiconductor switching circuit without spatial separation of drain and gate current loops.

FIG. 5B shows a schematic view of the semiconductor switching circuit of FIG. 5A.

FIGS. 6A-6D show a schematic view of current loops within the semiconductor switching circuit of FIG. 5B.

FIG. 7 shows a layout of a semiconductor switching circuit, in accordance with embodiments described herein.

FIG. 8A shows a layout view of a semiconductor switching circuit, in accordance with embodiments described herein.

FIG. 8B shows a schematic view of a semiconductor switching circuit, in accordance with embodiments described herein.



FIGS. 9A-9D show a schematic view of current loops within a semiconductor switching circuit, in accordance with embodiments described herein.

FIGS. 10A-10C show layout views of semiconductor switching circuits, in accordance with embodiments described herein.

FIG. 11 shows a layout of a semiconductor switching circuit, in accordance with embodiments described herein.

FIG. 12 shows a layout of a semiconductor switching circuit, in accordance with embodiments described herein.

FIG. 13 shows a layout of a semiconductor switching circuit, in accordance with embodiments described herein.

FIG. 14 shows a layout of a semiconductor switching circuit, in accordance with embodiments described herein.

FIG. 15A shows a layout of a semiconductor switching circuit, in accordance with embodiments described herein.

FIG. 15B shows a layout of a semiconductor switching circuit, in accordance with embodiments described herein.

FIG. 16 shows a layout of a semiconductor switching circuit, in accordance with embodiments described herein.

FIG. 17 shows a layout of a semiconductor switching circuit, in accordance with embodiments described herein.

FIGS. 18A and 18B illustrate gate connections between paralleled transistors, in accordance with embodiments described herein.

FIG. 19 shows a cross-sectional view of a portion of a printed circuit board including parallel transistors, in accordance with embodiments described herein.

FIG. 20 shows a cross-sectional view of a portion of a printed circuit board including parallel transistors, in accordance with embodiments described herein.

FIG. 21 shows a layout of a semiconductor converter circuit, in accordance with embodiments described herein.

FIG. 22 shows a layout of a semiconductor converter circuit, in accordance with embodiments described herein.

FIG. 23 shows a layout of a semiconductor converter circuit, in accordance with embodiments described herein.

## DETAILED DESCRIPTION

In the following detailed description, reference is made to certain embodiments. These embodiments are described with sufficient detail to enable those skilled in the art to practice them. It is to be understood that other embodiments may be employed and that various structural, logical, and electrical changes may be made.

Embodiments described herein provide circuitry and methods of operation for parallel transistor devices. Techniques and geometries for reducing the undesirable effects of common source inductance (CSI) in parallel devices, such as GaN transistor devices, are described herein. Described embodiments include transistor circuits with layouts that provide spatial separation of the gate and drain current loops. The layout designs ensure that the currents between these loops remain perpendicular to each other, and thus remain decoupled. Other described embodiments include electrical connections, printed circuit board (PCB) layouts, and other features that can further reduce the impact of common source inductance experienced by transistor devices within the circuit.

While embodiments described herein may be described in connection with certain types of transistor devices, such as GaN transistor devices, it should be understood that the invention is not so limited. For example, the described embodiments may be applicable to transistor devices and other types of semiconductor devices that use different conductive materials, such as, for example, silicon (Si) or silicon-

containing materials, graphene, germanium (Ge), gallium arsenide (GaAs). Described embodiments are also applicable to other types of semiconductor devices, such as other field effect transistor (FET)-type semiconductor devices (e.g., metal-oxide semiconductor FETs (MOSFETs), junction-gate semiconductor FETs (JFETs), etc.), bipolar junction transistor (BJT) devices, and insulated-gate bipolar transistor (IGBT) devices. The described concepts are also equally applicable to silicon-on-oxide (SOI) transistor devices. In addition, the described concepts are equally applicable to both enhancement mode and depletion mode transistor devices. In addition, while specific embodiments are described in connection with paralleled switching devices, it should be understood that features described herein are generally applicable to other types of circuits, such as RF amplifiers, switching converters, devices of different yet similar physical structure, and other circuits.

FIGS. 4A and 4B show simplified schematics representing gate loops for a transistor device (e.g., device Q<sub>1</sub> of FIG. 3). FIG. 4A has been simplified to show the parasitic elements that can affect the transistor device's immunity to a change in voltage dv/dt, and simplifies to a current divider. FIG. 4B has been simplified to show the parasitic elements that can affect the transistor device's immunity to a change in current di/dt, and simplifies to a voltage divider.

Applicants have derived an empirical formula—Equation 1, representing the simplified form for di/dt immunity for switching devices:

$$\frac{di}{dt} = \frac{V_{th} \cdot \left[ 1 + R_g + R_{DR} + \frac{\sqrt{L_g \cdot C_{gs}}}{L_g + C_{gs}} \right]}{L_s} \quad \text{Equation 1}$$

In Equation 1, di/dt is the rate of change in current through source inductor [measured in Amperes per second], V<sub>th</sub> is the threshold voltage of the switch [measured in Volts], R<sub>g</sub> is the gate resistance [measured in ohms], R<sub>DR</sub> is the gate driver output resistance [measured in ohms], L<sub>g</sub> is the gate inductance [measured in henries], C<sub>gs</sub> is the gate-to-source capacitance [measured in Farads], and L<sub>s</sub> is the source inductance [measured in henries]. Equation 1 applies to both single transistor devices and to multiple paralleled transistors.

Applicants have derived an empirical formula—Equation 2, representing the simplified form for dv/dt immunity for switching devices:

$$\frac{dv}{dt} = \frac{V_{th}}{C_{gd} \cdot \left[ R_g + R_{DR} + \sqrt{\frac{(L_g + L_s)}{C_{gs}}} \right]} \quad \text{Equation 2}$$

In Equation 2, dv/dt is the rate of change in voltage across drain-source [measured in Volts per second], V<sub>th</sub> is the threshold voltage of the switch [measured in Volts], C<sub>gd</sub> is the gate-to-drain capacitance [measured in Farads], R<sub>g</sub> is the gate resistance [measured in ohms], R<sub>DR</sub> is the gate driver output resistance [measured in ohms], L<sub>g</sub> is the gate inductance [measured in henries], C<sub>gs</sub> is the gate-to-source capacitance [measured in Farads], and L<sub>s</sub> is the source inductance [measured in henries].

Through a detailed analyses and simulations of these and other circuits, Applicants have determined several considerations for the paralleling of transistor devices, and in particu-

lar, paralleling GaN transistor devices. One consideration is that the source inductance must be maintained as low as possible, including by increasing drain inductance if necessary. Another consideration is that the gate inductance will usually always be higher than the source inductance (often with ratios at or exceeding 10:1), due to the narrow width and length of the gate driver transmission line from the gate driver to the gate of the transistor device. Another consideration is that the gate driver source and sink impedance can be configured to further improve switching performance using  $dv/dt$  reduction, but this may be detrimental to the efficiency of the switching circuit. Another consideration is that a complete solution, including gate inductance, results in a third order differential system (i.e.,  $d^3/dt^3$ ) with both sinusoidal and exponential terms that require a numerical analysis for a solution.

The conflicting requirements for controlling the change in voltage across a switching device ( $dv/dt$ ) and change in current through the switching device ( $di/dt$ ) can be addressed by designs that yield a lowest possible CSI, thereby reducing its effect on the gates of the circuits. In particular, because GaN transistors typically have lower drive voltage capability, lower gate resistance, and lower capacitances than corresponding MOSFET devices, the effect of the common source inductance and  $dv/dt$  induced current on the gate circuit on transistors using GaN transistors are much more pronounced than in devices utilizing MOSFETs. The physical layouts of the gates of the transistors can be arranged to be electrically close to yield the lowest possible inductance.

Prior to describing embodiments of the present invention, a description will be given of the operation of common source inductance on a circuit including parallel transistor devices. FIG. 5A is a top-down view of a circuit 200 including two sets of paralleled semiconductor devices,  $Q_{upper1}$  and  $Q_{upper2}$ , and  $Q_{lower1}$  and  $Q_{lower2}$ , arranged in a half-bridge configuration. Circuit 200 may be used, for example, in a switching converter, or other types of circuits, particularly those in which high current capability and/or heat dissipation spreading is desirable, such as part of circuit 120 in FIG. 2. Circuit 200 includes four transistor devices, such as GaN FETs, including first and second upper transistor devices  $Q_{upper1}$  and  $Q_{upper2}$  arranged in parallel, and first and second lower transistor devices  $Q_{lower1}$  and  $Q_{lower2}$  arranged in parallel. First and second upper transistor devices  $Q_{upper1}$  and  $Q_{upper2}$  and first and second lower transistor devices  $Q_{lower1}$  and  $Q_{lower2}$  may be, for example, enhancement or depletion mode semiconductor devices, such as GaN HEMT semiconductor devices, or any other suitable type of transistor device.

Circuit 200 also includes a supply decoupling elements 302 and 304, for decoupling circuit 200 from electrical interference of a power supply, adjacent circuitry and/or other elements and to buffer high currents of short duration from the main supply to provide a stable high frequency-capable DC supply to the transistor devices. Supply decoupling elements 302, 304 may be, for example, physical capacitors, such as multilayer type ceramic capacitors (MLCC). Gate driver transfer lines 305, 306 run perpendicular to the lengthwise direction of the respective upper set of transistors  $Q_{upper1}$ ,  $Q_{upper2}$  and lower set of transistors  $Q_{lower1}$ , and  $Q_{lower2}$ . FIG. 5A also includes a plurality of current loops 311-318 that are present during operation of circuit 200, which are described in further detail in connection with FIGS. 6A-6D below.

FIG. 5B is a schematic diagram illustrating physical and parasitic circuit elements in circuit 200. Circuit 200 includes a switch output connection 368 through which a drain-source

current is output from circuit 200, and a gate return connection 366. Circuit 200 also includes connections to gate transfer control lines 305, 306.

Upper transistor devices  $Q_{upper1}$  and  $Q_{upper2}$  include respective parasitic drain inductances  $L_{DU1}$  and  $L_{DU2}$ , respective parasitic gate inductances  $L_{GU1}$  and  $L_{GU2}$ , and respective parasitic source inductances  $L_{SU1}$  and  $L_{SU2}$ . Upper transistor devices  $Q_{upper1}$  and  $Q_{upper2}$  also include respective gate return inductances  $L_{GretU1}$  and  $L_{GretU2}$  between their respective sources and drains. Upper transistor devices  $Q_{upper1}$  and  $Q_{upper2}$  share a common source inductance  $L_{CSU}$ . In addition, upper transistor devices  $Q_{upper1}$  and  $Q_{upper2}$  share a common gate inductance  $L_{GateU}$ . A parasitic inter-connection inductance  $L_{CDecpU}$  is included between the respective drains of  $Q_{upper1}$  and  $Q_{upper2}$ .

Lower transistor devices  $Q_{lower1}$  and  $Q_{lower2}$  include respective parasitic source inductances  $L_{SL1}$  and  $L_{SL2}$ , and respective parasitic gate inductances  $L_{GL1}$  and  $L_{GL2}$ . Lower transistor devices  $Q_{lower1}$  and  $Q_{lower2}$  also include respective gate return inductances  $L_{GretL1}$  and  $L_{GretL2}$  between their respective sources and drains. Lower transistor devices  $Q_{lower1}$  and  $Q_{lower2}$  share a common source inductance  $L_{CSL}$ . In addition, lower transistor devices  $Q_{lower1}$  and  $Q_{lower2}$  share a common gate inductance  $L_{GateL}$ . A parasitic inter-connection inductance  $L_{CDecpL}$  is included between the respective sources of  $Q_{upper1}$  and  $Q_{upper2}$ .

Other elements shown in FIG. 5B include the respective capacitances  $C_{Decoup1}$ ,  $C_{Decoup2}$  of supply decoupling elements 302, 304 (FIG. 5A). Circuit 200 also includes respective parasitic equivalent series inductances  $L_{ESL1}$ ,  $L_{ESL2}$  for supply decoupling elements 302, 304. Other parasitic elements include the inductance of the switch node connection  $L_{SW}$ , the inductance of the output return  $L_{Oret}$ , the inductance between the respective first and second upper and lower loops  $L_{ULloop1}$ ,  $L_{ULloop2}$ , and the ground decoupling connection inductance of lower transistors  $L_{Decoup}$ . Although not shown in FIG. 5B, each transistor device  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{lower1}$ , and  $Q_{lower2}$  would typically also include parasitic source-drain, gate-source, and gate-drain capacitances, as shown in FIG. 3.

As discussed above in connection with FIG. 5A, circuit 200 also includes a plurality of current loops 311-318 that are present during operation of circuit 200. FIGS. 6A-6D illustrate these current loops on the schematic representation of circuit 200 shown in FIG. 5B.

For example, FIG. 6A shows respective upper switch inter-device current loop 311 within the upper set of parallel of transistors  $Q_{upper1}$  and  $Q_{upper2}$ , and lower switch inter-device current loop 312 within the lower parallel sets of transistors  $Q_{lower1}$  and  $Q_{lower2}$ . Upper and/or lower switch inter-device current loops 311, 312 may manifest when an imbalance occurs between the paralleled transistor devices, for example due to small differences in device parameters (e.g., respective threshold voltages  $V_{th}$ ). FIG. 6B shows respective first and second side supply decoupling current loops 313, 314, representing the path that a supply current travels between supply decoupling element 302 (FIG. 5A) and the set of first side transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$ , and supply decoupling element 304 (FIG. 5A) and the set of second side transistor devices  $Q_{upper2}$ ,  $Q_{lower2}$ , respectively.

FIG. 6C shows an upper first side supply-to-load current loop 315 representing the path that current takes from first side upper transistor device  $Q_{upper1}$  to the switch output node 368, and an upper second side supply-to-load current loop 317 presenting the path that current takes from second side upper transistor device  $Q_{upper2}$  to switch output node 368. FIG. 6D shows a lower first side return-to-load current loop

316 representing the path that current takes from first side lower transistor device  $Q_{lower1}$  to the switch output node 368, and a lower second side return-to-load current loop 318 representing the path that current takes from second side lower transistor device  $Q_{lower1}$  to switch output node 368. As shown in FIGS. 6C and 6D, there is a net current (i.e., from upper first side supply-to-load current loop 315 and lower first side return-to-load current loop 316) flowing in upper common source inductance  $L_{CSIU}$ .

As shown in FIG. 5A, first and second upper transistor devices  $Q_{upper1}$  and  $Q_{upper2}$  and first and second lower transistor devices  $Q_{lower1}$  and  $Q_{lower2}$  are arranged lengthwise to one another, respectively, with upper first side supply-to-load current loop 315, lower first side return-to-load current loop 316, upper second side supply-to-load current loop 317, and lower second side return-to-load current loop 318 flowing parallel to the upper switch inter-device current loop 311, the lower switch inter-device current loop 312, and the first and second side supply decoupling current loops 313, 314. Upper first side supply-to-load current loop 315 and upper second side supply-to-load current loop 317 form a drain current for the upper set of first and second upper transistor devices  $Q_{upper1}$  and  $Q_{upper2}$ , and lower first side return-to-load current loop 316 and lower second side return-to-load current loop 318 form a drain current for the lower set of first and second lower transistor devices  $Q_{lower1}$  and  $Q_{lower2}$ .

While the circuit 200 shown in FIG. 5A includes a low supply inductance relative to design layouts described below due to its long narrow layout, circuit 200 exhibits an inferior immunity to transient currents  $di/dt$  due to CSI. Returning to FIGS. 6A-6D, upper transistor devices  $Q_{upper1}$  and  $Q_{upper2}$  share a common source inductance  $L_{CSIU}$ , and lower transistor devices  $Q_{lower1}$  and  $Q_{lower2}$  share a common source inductance  $L_{CSIL}$ . As shown in FIG. 6C, with the drain currents of circuit 200 flowing in parallel with the gate source path, upper first side supply-to-load current loop 315 flows through the upper common source inductance  $L_{CSIU}$  to switch node 368, while upper second side supply-to-load current loop 317 flows from a source of  $Q_{upper2}$  to switch node 368. As shown in FIG. 6D, lower first side return-to-load current loop 316 flows through the lower common source inductance  $L_{CSIL}$  and upper common source inductance  $L_{CSIU}$  to switch node 368, while lower second side return-to-load current loop 318 flows from a drain of  $Q_{lower2}$  to switch node 368.

Varying current levels flowing through upper and lower common source inductances  $L_{CSIU}$ ,  $L_{CSIL}$ , such as from transient currents  $di/dt$  flowing through devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{lower1}$ , and  $Q_{lower2}$ , can induce a voltage ( $V_{di/dt}$ ) across the respective source inductances  $L_{CSIU}$  and  $L_{CSIL}$ . Because a voltage generated at the common source inductance also affects the common gate voltage of transistors  $Q_{upper1}$  and  $Q_{upper2}$ , and the common gate voltage of transistors  $Q_{lower1}$  and  $Q_{lower2}$ , a change of drain current  $I_{L\_CSI}$  (e.g., during transient events) induces a voltage on the respective gate-source circuits of transistors  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{lower1}$ , and  $Q_{lower2}$ . Accordingly, the design shown in FIG. 5A exhibits a relatively low immunity to transient currents, compared to embodiments described below.

FIG. 7 shows one embodiment of a layout of a transistor circuit 500 for reducing the undesirable effects of common source inductance (CSI) in parallel devices. Circuit 500 may be, for example, a semiconductor switching circuit that includes parallel upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$  and parallel lower transistor devices  $Q_{lower1}$  and  $Q_{lower2}$ , arranged in a half-bridge configuration. Transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{lower1}$ ,  $Q_{lower2}$  can be formed on a top surface of a printed circuit board (PCB), and are arranged

vertically widthwise from one another with the same orientation. Circuit 500 includes first and second supply decoupling elements 601, 602, which can be formed on a bottom side of the PCB.

Circuit 500 also includes respective upper and lower gate driver transfer lines 603, 605. In circuit 500, gate driver transfer lines 603, 605 are perpendicular to the respective upper set of transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$  and lower set of transistor devices  $Q_{lower1}$ , and  $Q_{lower2}$ . Output current path 608 runs in a lengthwise direction to the transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{lower1}$ ,  $Q_{lower2}$  of circuit 500. Circuit 500 provides a  $90^\circ$  (i.e., perpendicular) spatial separation between the respective output current path 608 (which may be, for example, a source-to-drain current path) and common source inductance current path 606 which is common to the gate current path. The spatial separation between a common source inductance current path 606 and output current path 608 decouples the common source inductance current path 606 from the output current path 608, thereby increasing immunity of circuit 500 to variation on the gate voltage experienced due to transient currents causing a voltage on the common source inductance. Transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{lower1}$ ,  $Q_{lower2}$  of circuit 500 are arranged such that the respective gates of the transistor devices are electrically close to one another. For example, the gates are arranged such that a distance between respective gates is less than three times the distance of the smallest physical dimension of the transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{lower1}$ ,  $Q_{lower2}$  of circuit 500. For example, the distance between the respective gates of  $Q_{upper1}$  and  $Q_{upper2}$ , may be less than three times the magnitude of the shorter of the width or length of one of  $Q_{upper1}$  or  $Q_{upper2}$ . Alternatively, traces that are wider than the width of the gate pad of the respective transistor device may be used to also yield electrically close connections at the gates of the respective transistor devices.

FIG. 8A illustrates a top view of the design layout of transistor circuit 500, showing current loops 611-618 within circuit 500. As shown in FIG. 8A, first and second upper transistor devices  $Q_{upper1}$  and  $Q_{upper2}$  and first and second lower transistor devices  $Q_{lower1}$  and  $Q_{lower2}$  are arranged widthwise to one another, respectively, with upper first side supply-to-load current loop 615, upper first side return-to-load current loop 616, lower second side supply-to-load current loop 617, and lower second side return-to-load current loop 618 flowing perpendicular to the upper switch inter-device current loop 611, the lower switch inter-device current loop 612, and the first and second side supply decoupling current loops 613, 614. First side supply-to-load current loop 615, first side return-to-load current loop 617, second side supply-to-load current loop 616 and second side return-to-load current loop 618 form the switch output current 608.

FIG. 8B illustrates a schematic view of transistor circuit 500. Circuit 500 includes a switch output connection 568 through which a drain-source current is output from circuit 200, and a gate return connection 566. Circuit 500 also includes connections to gate transfer control lines 603, 605.

Upper transistor devices  $Q_{upper1}$  and  $Q_{upper2}$  include respective parasitic drain inductances  $L_{DU1}$  and  $L_{DU2}$ , respective parasitic gate inductances  $L_{GU1}$  and  $L_{GU2}$ , and respective parasitic source inductances  $L_{SU1}$  and  $L_{SU2}$ . Upper transistor devices  $Q_{upper1}$  and  $Q_{upper2}$  also include respective gate return inductances  $L_{GretU1}$  and  $L_{GretU2}$  between their respective sources and drains. Upper transistor devices  $Q_{upper1}$  and  $Q_{upper2}$  share a common source inductance  $L_{CSIU}$ . In addition, upper transistor devices  $Q_{upper1}$  and  $Q_{upper2}$  share a common gate inductance  $L_{GateU}$ . A parasitic

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inter-connection inductance  $L_{CDepU}$  is included between the respective drains of  $Q_{upper1}$  and  $Q_{upper2}$ .

Lower transistor devices  $Q_{lower1}$  and  $Q_{lower2}$  include respective parasitic source inductances  $L_{SL1}$  and  $L_{SL2}$ , and respective parasitic gate inductances  $L_{GL1}$  and  $L_{GL2}$ . Lower transistor devices  $Q_{lower1}$  and  $Q_{lower2}$  also include respective gate return inductances  $L_{GretL1}$  and  $L_{GretL2}$  between their respective sources and drains. Lower transistor devices  $Q_{lower1}$  and  $Q_{lower2}$  share a common source inductance  $L_{CSL}$ . In addition, lower transistor devices  $Q_{lower1}$  and  $Q_{upper2}$  share a common gate inductance  $L_{GateL}$ . A parasitic inter-connection inductance  $L_{CDepL}$  is included between the respective sources of  $Q_{upper1}$  and  $Q_{upper2}$ .

Other elements shown in FIG. 8B include the respective capacitances  $C_{Decoup1}$ ,  $C_{Decoup2}$  of supply decoupling elements **601**, **602**, as well as respective parasitic equivalent series inductances  $L_{ESL1}$ ,  $L_{ESL2}$  for supply decoupling elements **601**,  $602$ . Circuit **500** also includes the respective inductances between the first and second upper and lower loops  $L_{ULoop1}$ ,  $L_{ULoop2}$ , and the ground decoupling connection inductance of lower transistor devices  $L_{Decoup}$ . Circuit **500** also includes respective parasitic inductances  $L_{SW1}$ ,  $L_{SW2}$  for the first and second sides' connection to the switch output connection **568**, and respective parasitic inductances  $L_{Oret1}$ ,  $L_{Oret2}$  for the first and second sides' connection to the switch return connection **566**.

FIGS. 9A-9D illustrate the current loops **611-618** on the schematic representation of circuit **500** in FIG. 8B. FIG. 9A shows upper switch inter-device current loop **611** representing the path that current travels within the upper set of parallel of transistor devices  $Q_{upper1}$  and  $Q_{upper2}$ , and lower switch inter-device current loop **612** representing the path that current travels within the lower parallel sets of transistors  $Q_{lower1}$  and  $Q_{lower2}$ . FIG. 9B shows respective first and second side supply decoupling current loops **613**, **614**, representing the respective paths that current travels between supply decoupling element **601** (FIG. 8A) and the set of first side transistors  $Q_{lower1}$  and  $Q_{upper1}$  and between supply decoupling element **602** (FIG. 8A) and the set of second side transistors  $Q_{lower2}$  and  $Q_{upper2}$ .

FIG. 9C shows a first side supply-to-load current loop **615**, representing the path that current takes from first side upper transistor device  $Q_{upper1}$  to switch output node **568**, and second side supply-to-load current loop **617**, representing the path that current takes from second side upper transistor device  $Q_{upper2}$  to switch output node **568**. FIG. 9D shows a first side return-to-load current loop **616**, representing the path that current takes from first side lower transistor device  $Q_{lower1}$  to switch output node **568**, and a second side return-to-load current loop **618**, representing the path that current takes from second side lower transistor device  $Q_{lower2}$  to switch output node **568**.

As shown in FIG. 9C, first side supply-to-load current loop **615** from first side upper transistor device  $Q_{upper1}$  and second side supply-to-load current loop **617** from second side upper transistor device  $Q_{upper2}$  are balanced across opposite sides of circuit **500**. Similarly, as shown in FIG. 9D, return-to-load current loop **616** from first side lower transistor device  $Q_{lower1}$  and second side supply-to-load current loop **617** from second side upper transistor device  $Q_{upper2}$  are balanced across opposite sides of circuit **500**. Accordingly, the main output current for circuit **500** (e.g., the current in output current path **608**) will flow in opposite directions at the same time, thereby balancing any voltage that results from variations in current di/dt across the common source of circuit **500**. Although some imbalance between di/dt induced voltages may remain, the resultant voltage will be significantly smaller

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than in conventional arrangements. As shown in both FIGS. 9C and 9D, the respective voltages generated in each of inductances  $L_{SW1}$  and  $L_{SW2}$  will essentially have the same magnitude, given the same values of  $L_{SW1}=L_{SW2}$  by geometric symmetry of the layout and assumed current sharing from each of the loops **615** and **617** (FIG. 9C) and loops **616** and **618** (FIG. 9D). The total voltage across both inductances  $L_{SW1}$  and  $L_{SW2}$  will then equate to zero, thereby ensuring that the output current is decoupled from the common source inductance of each of the devices.

FIGS. 10A-10C illustrates variations on the design shown in FIG. 7 for circuits including different numbers of transistor devices with electrically close gate connections.

In FIG. 10A, circuit **530** includes two paralleled upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ , and two paralleled lower transistor devices  $Q_{lower1}$ , and  $Q_{lower2}$ . Unlike in circuit **500** of FIG. 7, however, paralleled upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$  are arranged lengthwise to one another with opposite orientations, as are paralleled lower transistor devices  $Q_{lower1}$  and  $Q_{lower2}$ . Gate driver transfer line **633** is commonly coupled to the gates of first and second upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$  in a T structure configuration, and gate transfer line **635** is commonly coupled to the gates of first and second lower transistor devices  $Q_{lower1}$ ,  $Q_{lower2}$  in another T structure configuration. Two supply decoupling elements **631**, **632** corresponding to first side transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$  are located on a bottom side of a PCB, and two supply decoupling elements **634**, **636** corresponding to second side transistor devices  $Q_{upper2}$ ,  $Q_{lower2}$  are located on the bottom side of the PCB. An output current path **638** runs lengthwise the devices in circuit **530**.

In FIG. 10B, circuit **540** includes three paralleled upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{upper3}$ , and three paralleled lower transistor devices  $Q_{lower1}$ ,  $Q_{lower2}$ ,  $Q_{lower3}$ . Paralleled upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{upper3}$  are arranged lengthwise to one another, as are paralleled lower transistor devices  $Q_{lower1}$ ,  $Q_{lower2}$ ,  $Q_{lower3}$ . Gate driver transfer line **643** is commonly coupled to the gates of first, second, and third upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{upper3}$  in an H structure configuration, and gate transfer line **645** is commonly coupled to the gates of first, second, and third lower transistor devices  $Q_{lower1}$ ,  $Q_{lower2}$ ,  $Q_{lower3}$  in another H structure configuration. Two supply decoupling elements **641**, **642** corresponding to first side transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$  are located on a bottom side of a PCB, and two supply decoupling elements **644**, **646** corresponding to second and third side transistor devices  $Q_{upper2}$ ,  $Q_{lower2}$ ,  $Q_{upper3}$ ,  $Q_{lower3}$  are located on the bottom side of the PCB. An output current path **648** runs lengthwise the devices in circuit **540**.

In FIG. 10C, circuit **550** includes four paralleled upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{upper3}$ ,  $Q_{upper4}$ , and four paralleled lower transistor devices  $Q_{lower1}$ ,  $Q_{lower2}$ ,  $Q_{lower3}$ ,  $Q_{lower4}$ . Paralleled upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{upper3}$ ,  $Q_{upper4}$  are arranged lengthwise to one another, as are paralleled lower transistor devices  $Q_{lower1}$ ,  $Q_{lower2}$ ,  $Q_{lower3}$ ,  $Q_{lower4}$ . Gate driver transfer line **653** is commonly coupled to the gates of first, second, third, and fourth upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{upper3}$ ,  $Q_{upper4}$  in an H structure configuration, and gate transfer line **655** is commonly coupled to the gates of first, second, third, and fourth lower transistor devices  $Q_{lower1}$ ,  $Q_{lower2}$ ,  $Q_{lower3}$ ,  $Q_{lower4}$  in another H structure configuration. Two supply decoupling elements **651**, **652** corresponding to first and second side transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$ ,  $Q_{upper2}$ ,  $Q_{lower2}$  are located on a bottom side of a PCB, and two supply decoupling elements **654**, **656** corresponding to third and fourth side transistor devices  $Q_{upper3}$ ,  $Q_{lower3}$ ,  $Q_{upper4}$ ,  $Q_{lower4}$  are located on the

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bottom side of the PCB. An output current path **658** runs lengthwise the devices in circuit **550**.

FIG. **11** illustrates another layout design for a circuit **700** including paralleled transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$ ,  $Q_{upper2}$ ,  $Q_{lower2}$  with electrically close gate connections. Paralleled upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$  are arranged on a first side of circuit **700**, and paralleled lower transistor devices  $Q_{lower1}$ ,  $Q_{lower2}$  are arranged on a second side, with upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$  arranged widthwise to lower transistor devices  $Q_{lower1}$ ,  $Q_{lower2}$ . First and second supply decoupling elements **701**, **702** are arranged on the same side of a PCB as the transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$ ,  $Q_{upper2}$ ,  $Q_{lower2}$ . Respective upper and lower gate driver transfer lines **703**, **705** run perpendicular to the respective upper set of transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$  and lower set of transistor devices  $Q_{lower1}$ , and  $Q_{lower2}$ . An output current path **708** runs in a widthwise direction to the transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$ ,  $Q_{upper2}$ ,  $Q_{lower2}$  of circuit **700**. Circuit **700** provides a  $90^\circ$  (i.e., perpendicular) spatial separation between the respective output current path **708** (which may be, for example, a source-to-drain current path) and the inter-device inductance current direction **706**.

FIG. **12** illustrates another layout design for a circuit **800** including paralleled transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$ ,  $Q_{upper2}$ ,  $Q_{lower2}$  with electrically close gate connections. In circuit **800**, transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$ ,  $Q_{upper2}$ ,  $Q_{lower2}$  are located on a top side of a PCB, while supply decoupling elements **801**, **802** are located on a bottom side of the PCB. Upper and lower gate driver transfer lines **803**, **805** are perpendicular to the respective upper set of transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$  and lower set of transistor devices  $Q_{lower1}$ ,  $Q_{lower2}$ . An output current path **808** runs in a lengthwise direction to the transistor devices in circuit **800**. Circuit **800** provides a  $90^\circ$  (i.e., perpendicular) spatial separation between the respective output current path **808** (which may be, for example, a source-to-drain current path) and the inter-device inductance current direction **806**. Preferably, circuit **800** maintains a width  $w$  spanning from gate driver transfer lines **803**, **805** to an output node that is greater than a length  $l$  spanning parallel transistors (e.g.,  $Q_{lower1}$  and  $Q_{lower2}$ ). Maintaining this configuration provides a lower inter-device source inductance for circuit **800**.

FIG. **13** illustrates another layout design for a circuit **900** including paralleled transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$ ,  $Q_{upper2}$ ,  $Q_{lower2}$  with electrically close gate connections. As in circuit **700** of FIG. **11**, paralleled upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$  are arranged on a first side of circuit **700**, and paralleled lower transistor devices  $Q_{lower1}$ ,  $Q_{lower2}$  are arranged on a second side, with upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$  arranged widthwise to lower transistor devices  $Q_{lower1}$ ,  $Q_{lower2}$ . In circuit **900**, however, transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$ ,  $Q_{upper2}$ ,  $Q_{lower2}$  are located on a top side of a PCB, while supply decoupling elements **901**, **902** are located on a bottom side of the PCB. Upper and lower gate driver transfer lines **903**, **905** run parallel to the respective upper set of transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$  and lower set of transistor devices  $Q_{lower1}$ , and  $Q_{lower2}$ . The output current path **908** runs in a widthwise direction to circuit **900**. Circuit **900** provides a  $90^\circ$  (i.e., perpendicular) spatial separation between the respective output current path **908** (which may be, for example, a source-to-drain current path) and the inter-device inductance current direction **906**. Preferably, circuit **900** maintains a width  $w$  that is greater than a length  $l$ , in order to provide a lower inter-device source inductance for circuit **900**.

FIG. **14** illustrates another layout design for a circuit **1000** including paralleled transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$ ,

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$Q_{upper2}$ ,  $Q_{lower2}$ ,  $Q_{upper3}$ ,  $Q_{lower3}$ ,  $Q_{upper4}$ ,  $Q_{lower4}$ . In circuit **1000**, paralleled upper transistors  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{upper3}$ ,  $Q_{upper4}$ , and paralleled lower transistors  $Q_{lower1}$ ,  $Q_{lower2}$ ,  $Q_{lower3}$ ,  $Q_{lower4}$ , are located on a top side of a PCB, while supply decoupling elements **1001**, **1002** are located on a bottom side of the PCB. Circuit **1000** includes respective upper and lower gate driver transfer lines **1003**, **1005** that form electrically close gate connections. The commonly-connected gates of paralleled upper transistors  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{upper3}$ ,  $Q_{upper4}$  are coupled using a Y-T structure, as are the commonly-connected gates of paralleled lower transistors  $Q_{lower1}$ ,  $Q_{lower2}$ ,  $Q_{lower3}$ ,  $Q_{lower4}$ .

Three current paths **1006**, **1007**, **1008** are shown in FIG. **14**. An output current path **1008** flows lengthwise to transistor devices in circuit **1000**. A first inter-device current path **1006** flows width-wise to transistor devices in circuit **1000**, and at a  $90^\circ$  (i.e., perpendicular) angle to the output current path **1008**. A second inter-device current **1007** flows parallel to the output current path **1008**. In one embodiment, a first width  $w$  is greater than a first length  $l$ . In another embodiment, a second width  $w_2$  that is greater than the second length  $l_2$ .

If, in circuit **1000**, a lower source inductance is yielded by the first embodiment (i.e., with a first width  $w$  that is greater than a first length  $l$ ), then first inter-device current path **1006** corresponds to output current path **1008**. If, however, a lower source inductance is yielded by the second embodiment (i.e., a second width  $w_2$  that is greater than the second length  $l_2$ ), then current path **1006** would effectively become the output current path, and inter-device current path **1007** represents the source inductance path.

FIG. **15A** illustrates another layout design for a circuit **1100** including paralleled transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$ ,  $Q_{upper2}$ ,  $Q_{lower2}$ ,  $Q_{upper3}$ ,  $Q_{lower3}$ ,  $Q_{upper4}$ ,  $Q_{lower4}$ . In circuit **1100**, for paralleled upper transistors  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{upper3}$ ,  $Q_{upper4}$ , a first set of upper transistors (e.g.,  $Q_{upper1}$ ,  $Q_{upper2}$ ) are located on a top side of a PCB, and a second set of upper transistors (e.g.,  $Q_{upper3}$ ,  $Q_{upper4}$ ) are located on a bottom side of the PCB. Similarly, for paralleled lower transistors  $Q_{lower1}$ ,  $Q_{lower2}$ ,  $Q_{lower3}$ ,  $Q_{lower4}$ , a first set of lower transistors (e.g.,  $Q_{lower1}$ ,  $Q_{lower2}$ ) are located on the top side of the PCB, and a second set of upper transistors (e.g.,  $Q_{lower3}$ ,  $Q_{lower4}$ ) are located on the bottom side of the PCB. First and second supply decoupling elements **1101**, **1102** may be located on one or both sides of the PCB (e.g., first supply decoupling element **1101** may be located on the top side of the PCB, and second supply decoupling element **1102** may be located on the bottom side of the PCB. In another embodiment, first and second supply decoupling elements **1101**, **1102** may be located on the top side of the PCB, and a third and a fourth supply decoupling element **1103**, **1104** may be located on the bottom side of the PCB. Parallel transistors on respective sides of the PCB (e.g.,  $Q_{upper1}$ ,  $Q_{upper2}$ ) are arranged widthwise to one another in opposing directional alignment, with the respective gate connections of the transistors on neighboring sides, to provide electrically close gate connections.

Respective upper and lower gate driver transfer lines **1105**, **1107** run parallel to the length of the respective transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$ ,  $Q_{upper2}$ ,  $Q_{lower2}$ ,  $Q_{upper3}$ ,  $Q_{lower3}$ ,  $Q_{upper4}$ ,  $Q_{lower4}$ . The commonly-connected gates of upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{upper3}$ ,  $Q_{upper4}$  are coupled by an x-structured connection, as are the commonly-connected gates of lower transistors  $Q_{lower1}$ ,  $Q_{lower2}$ ,  $Q_{lower3}$ ,  $Q_{lower4}$ . An output current direction **1108** runs width-wise to transistor devices in circuit **1100**, and an inter-device inductance current **1106** flows in a  $90^\circ$  (i.e., perpendicular) angle to the output current path **1108**. Preferably, circuit **1100** main-

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tains a width  $w$  that is greater than a length  $l$ , thereby yielding a low inductance for circuit **1100**.

FIG. **15B** illustrates another layout design for a circuit **1150** including paralleled transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$ ,  $Q_{upper2}$ ,  $Q_{lower2}$ ,  $Q_{upper3}$ ,  $Q_{lower3}$ ,  $Q_{upper4}$ ,  $Q_{lower4}$ . In circuit **1150**, for paralleled upper transistors  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{upper3}$ ,  $Q_{upper4}$ , a first set of upper transistors (e.g.,  $Q_{upper1}$ ,  $Q_{upper2}$ ) are located on a top side of a PCB, and a second set of upper transistors (e.g.,  $Q_{upper3}$ ,  $Q_{upper4}$ ) are located on a bottom side of the PCB. Similarly, for paralleled lower transistors  $Q_{lower1}$ ,  $Q_{lower2}$ ,  $Q_{lower3}$ ,  $Q_{lower4}$ , a first set of lower transistors (e.g.,  $Q_{lower1}$ ,  $Q_{lower2}$ ) are located on the top side of the PCB, and a second set of upper transistors (e.g.,  $Q_{lower3}$ ,  $Q_{lower4}$ ) are located on the bottom side of the PCB. Unlike circuit **1100** of FIG. **15A**, in circuit **1150** of FIG. **15B**, parallel transistors on respective sides of the PCB (e.g.,  $Q_{upper1}$ ,  $Q_{upper2}$ ) are arranged lengthwise to one another in the same directional alignment, with the respective gate connections of the transistors aligned with one another, to provide electrically close gate connections.

In circuit **1150**, respective upper and lower gate driver transfer lines **1155**, **1157** run parallel to the length of the respective transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$ ,  $Q_{upper2}$ ,  $Q_{lower2}$ ,  $Q_{upper3}$ ,  $Q_{lower3}$ ,  $Q_{upper4}$ ,  $Q_{lower4}$ . The commonly-connected gates of upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{upper3}$ ,  $Q_{upper4}$  are coupled by an x-structured connection, as are the commonly-connected gates of lower transistors  $Q_{lower1}$ ,  $Q_{lower2}$ ,  $Q_{lower3}$ ,  $Q_{lower4}$ . An output current direction **1158** runs lengthwise to transistor devices in circuit **1150**, and an inter-device inductance current **1156** flows in a  $90^\circ$  (i.e., perpendicular) angle to the output current path **1158**. Preferably, circuit **1150** maintains a width  $w$  that is greater than a length  $l$ , thereby yielding a low inductance for circuit **1150**.

FIG. **16** illustrates another layout design for a circuit **1200** including paralleled transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$ ,  $Q_{upper2}$ ,  $Q_{lower2}$ ,  $Q_{upper3}$ ,  $Q_{lower3}$ ,  $Q_{upper4}$ ,  $Q_{lower4}$  with electrically close gate connections. In circuit **1200**, paralleled upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{upper3}$ ,  $Q_{upper4}$  are located on a first side (e.g., a top side) of a PCB, and paralleled lower transistors  $Q_{lower1}$ ,  $Q_{lower2}$ ,  $Q_{lower3}$ ,  $Q_{lower4}$  are located on a second side (e.g., a bottom side) of the PCB. Circuit **1200** includes first and second supply decoupling elements **1201**, **1202** on a first side of the PCB, and third and fourth supply decoupling elements **1203**, **1204** on a second side of the PCB.

In circuit **1200**, respective upper and lower gate driver transfer lines **1205**, **1207** run perpendicular to the length of the respective transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$ ,  $Q_{upper2}$ ,  $Q_{lower2}$ ,  $Q_{upper3}$ ,  $Q_{lower3}$ ,  $Q_{upper4}$ ,  $Q_{lower4}$ . The commonly-connected gates of upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{upper3}$ ,  $Q_{upper4}$  are coupled by an H-structured connection, as are the commonly-connected gates of lower transistors  $Q_{lower1}$ ,  $Q_{lower2}$ ,  $Q_{lower3}$ ,  $Q_{lower4}$ . An output current path **1208** flows lengthwise to transistor devices in circuit **1200**.

FIG. **17** illustrates another layout design for a circuit **1300** including paralleled transistor devices  $Q_{upper1}$ ,  $Q_{lower1}$ ,  $Q_{upper2}$ ,  $Q_{lower2}$ ,  $Q_{upper3}$ ,  $Q_{lower3}$ ,  $Q_{upper4}$ ,  $Q_{lower4}$  with electrically close gate connections. In circuit **1300**, a first set of upper transistor devices (e.g., first and second upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ) and a first set of lower transistor devices (e.g., first and second lower transistor devices  $Q_{lower1}$ ,  $Q_{lower2}$ ) are located on a first side (e.g., a top side) of a PCB. A second set of upper transistor devices (e.g., third and fourth upper transistor devices  $Q_{upper3}$ ,  $Q_{upper4}$ ) and a second set of lower transistor devices (e.g., lower transistor devices  $Q_{lower3}$ ,  $Q_{lower4}$ ) are located on a second side (e.g., a bottom side) of the PCB. First and second supply decoupling ele-

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ments **1301**, **1302** are also located on the first side of the PCB, and third and fourth supply decoupling elements **1303**, **1304** are located on the second side of the PCB.

In circuit **1300**, paralleled upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{upper3}$ ,  $Q_{upper4}$  have their respective gates commonly coupled to upper gate driver transfer line **1305** using an X-structure connection, and paralleled lower transistor devices  $Q_{lower1}$ ,  $Q_{lower2}$ ,  $Q_{lower3}$ ,  $Q_{lower4}$  have their respective gates commonly coupled to lower gate driver transfer line **1307** using an X-structure connection.

FIGS. **18A** and **18B** show two different approaches to provide electrically close common connections between paralleled transistor devices. FIG. **18A** illustrates one example layout for paralleled transistor devices in a circuit **1200**, which may be, for example, a switching circuit. Circuit **1400** includes parallel upper transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$  and parallel lower transistor devices  $Q_{lower1}$  and  $Q_{lower2}$ . In FIG. **18A**, each of first upper transistor device  $Q_{upper1}$  and first lower transistor device  $Q_{lower1}$  includes two shorter sides  $a$ ,  $c$ , and two longer sides  $b$ ,  $d$ . Each of second upper transistor device  $Q_{upper2}$  and second lower transistor device  $Q_{lower2}$  includes two shorter sides  $e$ ,  $g$ , and two longer sides  $f$ ,  $h$ . For example, transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{lower1}$ , and  $Q_{lower2}$  may have a quadrangular or substantially rectangular footprint. It should be understood that, while other embodiments may depict transistor devices having shorter and/or longer sides, such as rectangular-shaped transistor devices, these devices are not drawn to scale and are not intended to be limited to any particular shape or footprint.

To further reduce the effects of common source inductance on operation of the circuit **1400**, respective shorter sides  $c$ ,  $e$  of upper transistor devices  $Q_{upper1}$  and  $Q_{upper2}$  are aligned, and respective shorter sides  $c$ ,  $e$  of lower transistor devices  $Q_{lower1}$  and  $Q_{lower2}$  are aligned, thereby forming the longest (in relation to the gate current path) and narrowest (in relation to the drain source current path) layout structure possible. Such an arrangement results in the drain source loop of circuit **1400** having very low impedance in relation to the gate source loop. This ensures that high transient currents flow in a predictable manner, and do not creep into and corrupt alternative paths, such as the gate source circuit.

Also in circuit **1400**, each transistor device  $Q_{upper1}$ ,  $Q_{upper2}$ ,  $Q_{lower1}$ , and  $Q_{lower2}$  includes a respective gate connection **1430**, **1440**, **1470**, **1480**, each of which may be, for example, conductive gate pads. In circuit **1400**, upper switch gate connections **1430**, **1440** are arranged at opposing corners of adjacent shorter sides  $c$ ,  $e$  of the respective footprints of transistor devices  $Q_{upper1}$ ,  $Q_{upper2}$ . Lower switch gate connections **1470**, **1480** are arranged at opposing corners of adjacent shorter sides  $c$ ,  $e$  of the respective footprints of transistor devices  $Q_{lower1}$ ,  $Q_{lower2}$ . It should be understood, however, that upper switch gate connections **1430**, **1440** and lower switch gate connections **1470**, **1480** need not be arranged at opposing corners, however. Indeed, future devices may include gate connections in a center of respective footprints of transistor devices. Such centered gates, used in the configuration of circuit **1400**, may further reduce common source inductance, and furthermore a centered gate may include source connections on either side of the gate pad, thereby further reducing inductance. Arranging the gate connections of paralleled transistor devices on adjacent sides provides for use of a starred electrical connection **1435** between first upper switch gate connector **1430** and second upper switch gate connector **1440**, where the starred connection includes a shared common node electrically connecting first upper switch gate connector **1430** and second upper switch gate connector **1440** to gate driver circuitry (e.g., to a

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gate driver voltage source). A starred electrical connection **1475** is also established between first lower switch gate connector **1470** and second lower switch gate connector **1480**, including a shared common node electrically connecting first lower switch gate connector **1470** and second lower switch gate connector **1480** to gate driver circuitry. The starred pattern helps to reduce the effects of the remaining inductance from the star point to the gate pad, due to the geometric symmetry of the gate connections.

While the long narrow structure of circuit **1400** in FIG. **18A** results in a drain source loop having very low impedance in relation to the gate loop, it also creates high inductance in circuit **1400**. FIG. **18B**, on the other hand, illustrates another example layout for paralleled transistor devices in a circuit **1500**, which may be, for example, a switching circuit. In circuit **1500**, parallel transistors  $Q_{upper1}$  and  $Q_{upper2}$  are arranged with a broad side  $b$  of  $Q_{upper1}$  facing a broad side  $h$  of  $Q_{upper2}$ . Parallel transistors  $Q_{lower1}$  and  $Q_{lower2}$  are arranged with a broad side  $d$  of  $Q_{lower1}$  facing a broad side  $f$  of  $Q_{lower2}$ . This short wide structure, where the gates **1530**, **1540** of paralleled upper transistors  $Q_{upper1}$  and  $Q_{upper2}$  are coupled using a first H-structure configuration **1535**, and the gates **1570**, **1580** of paralleled lower transistors  $Q_{lower1}$  and  $Q_{lower2}$  are coupled using a second H-structure configuration **1575**, provides a lower inter-device source inductance than circuit **1400** in FIG. **18A**.

FIG. **19** illustrates a cross-sectional view of a portion **1600** of a printed circuit board (PCB). PCB portion **1600** includes a top side, as well as multiple interior layers including layers **1-4**. Portion **1600** also includes an upper transistor device **910** and a lower transistor device **920** formed on a top side of the PCB.

As shown in FIG. **19**, connections to upper and lower transistor devices **910**, **920** can be assigned to different layers within PCB portion **1600**. Doing so can reduce capacitive coupling between the elements, such as an undesirable capacitive coupling on gate transmission lines. For upper transistor device **910**, PCB portion **1600** includes a positive supply voltage connection **912** in a first layer, a first output/gate return connection **914** in a second layer, a gate connection **916** in a third layer, and a second output/gate return connection **918** in a fourth layer. For lower transistor device **920**, PCB portion **1600** includes a first negative supply voltage connection **922** in a first layer, a gate connection **924** in a second layer, a second negative supply/gate return connection **926** in a third layer, and an output/gate return connection **928** in a fourth layer. In one embodiment, for upper transistor device **910**, positive supply voltage connection **912** may be connected to a drain of device **910**, and first output/gate return connection **914** and second output/gate return connection **918** may be connected to a source of device **910**. For lower transistor device **920**, first negative supply voltage connection **922** may be connected to a source of device **920**, and second negative supply/gate return connection **926** and output/gate return connection **928** may be connected to a source of device **920**.

Gate connection **916** for upper transistor device **910** is located between two electrically “quiet” layers, e.g., layers **2** and **4**, upon which first and second output/gate return connections **914**, **918** are formed. Electrically “quiet” refers to the relatively low voltage difference between two layers with respect to each other. This can include  $dv/dt$  as a consequence. Gate connection **924** for lower transistor device **920** is also located between two electrically “quiet” layers, e.g., layers **1** and **3**, upon which first and second negative supply connections **922**, **924** are formed.

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FIG. **20** illustrates a cross-sectional view of a portion **1700** of a dual-component-sided printed circuit board (PCB). PCB portion **1700** includes a top side, a bottom side, and multiple interior layers including layers **1-8**. Portion **1700** also includes an upper transistor device **930** formed on the top side of the PCB and a lower transistor device **966** formed on the bottom side of the PCB.

Connections to upper and lower transistor devices **930**, **966** can be assigned to different layers within PCB portion **1700**, to reduce capacitive coupling between the elements. For upper transistor device **930**, a positive supply connection **932** can be formed in a first layer, a first output/gate return connection **934** can be formed in a second layer, a first gate connection **936** can be formed in a third layer, second and third output/gate return connections **938**, **940** can be formed in a fourth layer and a fifth layer, respectively, a second gate connection **942** can be formed in a sixth layer, a fourth output/gate return connection **944** can be formed in a seventh layer, and a second positive supply connection **946** can be formed in an eighth layer. For lower transistor device **936**, a negative supply connection **950** can be formed in the first layer, a first gate connection **952** can be formed in the second layer, a first negative supply/gate return connection **954** can be formed in the third layer, first and second output/gate return connections **956**, **958** can be formed in the fourth and fifth layers, respectively, a second negative supply/gate return connection **960** can be formed in the sixth layer, a second gate connection **962** can be formed in the seventh layer, and a second negative supply connection **964** can be formed in the eighth layer.

In PCB portion **1700**, first gate connection **936** for upper transistor device **930** is located between two electrically “quiet” layers, e.g., layers **2** and **4**, upon which first and second output/gate return connections **934**, **938** are formed, and second gate connection **942** is located between two electrically “quiet” layers, e.g., layers **5** and **7**, upon which output/gate return connections **940** and **944** are formed. First gate connection **952** for lower transistor device **966** is also located between two electrically “quiet” layers, e.g., layers **1** and **3**, upon which first negative supply connections **950** and first negative supply/gate return connection **954** are formed, and second gate connection **962** is located between electrically “quiet” layers, e.g., layers **6** and **8**, upon which second negative supply/gate return connection **960** and second negative supply connection **964** are formed.

While certain embodiments described above have discussed paralleled transistor devices in connection with switching applications, other uses are also within the scope of this disclosure, including in converter circuits. For example, by way of reference, FIG. **21** illustrates a layout design for a circuit **2100** including a single transistor device  $Q_1$ . Circuit **2100** may be used, for example, in a converter circuit, such as a buck converter. Transistor device  $Q_1$  may be, for example, a GaN transistor device formed on a top side of a PCB, and acts as a synchronous rectifier for a buck converter formed from circuit **2100**. Circuit **2100** outputs an output current path **2208** widthwise to transistor device  $Q_1$ . Circuit **2100** also includes first and second supply decoupling elements **2102**, **2104**, which may be formed on a bottom side of the PCB. Circuit **2100** also includes an input switch **2110**, which may be, for example, another transistor device such as a GaN or MOSFET transistor device, and an input switch gate driver line **2112**. Transistor device  $Q_1$ , serving as a synchronous rectifier for circuit **2100**, is controlled by a gate transfer control line **2114**. In order to increase the circuit characteristics of converter circuits (e.g., increasing current-handling capabilities and/or heat loss distribution), paralleling of multiple transistor devices may be desired.

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FIG. 22 shows a layout design for a circuit 2200 including paralleled transistor devices  $Q_1$  and  $Q_2$ . Circuit 2200 may be used, for example, as a buck converter. Transistor devices  $Q_1$  and  $Q_2$  may be, for example, GaN transistor devices formed on a top side of a PCB, and connected in parallel act as a synchronous rectifier for a buck converter formed by circuit 2200. Circuit 2200 also includes first, second, and third supply decoupling elements 2202, 2204, 2206, which may be formed on a bottom side of the PCB. Circuit 2200 also includes an input switch 2210, which may be, for example, another transistor device such as a GaN or MOSFET transistor device, controlled by an input switch gate driver line 2212. Transistor devices  $Q_1$  and  $Q_2$ , serving as a synchronous rectifier for circuit 2200, are controlled by a gate transfer control line 2214 in an X-structure configuration. Paralleled transistor devices  $Q_1$  and  $Q_2$  are arranged vertically lengthwise to one another, and an output current path 2208 of circuit 2200 flows widthwise to the paralleled transistor devices  $Q_1$  and  $Q_2$  of circuit 2200.

FIG. 23 shows another layout design for circuit 2300 including paralleled transistor devices  $Q_1$  and  $Q_2$ , which may be used as part of a buck converter. Similar to circuit 2200 of FIG. 22, circuit 2300 includes transistor devices  $Q_1$  and  $Q_2$  that, in parallel, act as a synchronous rectifier for a buck converter formed by circuit 2300. Transistor devices  $Q_1$  and  $Q_2$  may be, for example, GaN transistor devices formed on a top side of a PCB. In contrast to circuit 2200, however, transistor devices transistor devices  $Q_1$  and  $Q_2$  of circuit 2300 are arranged vertically widthwise to one another, and are controlled by a gate transfer control line 2314 in an H-structure configuration. Circuit 2300 also includes first, second, and third supply decoupling elements 2302, 2304, 2306, which may be formed on a bottom side of the PCB. Circuit 2300 also includes an input switch 2310, which may be, for example, another transistor device such as a GaN or MOSFET transistor device, controlled by an input switch gate driver line 2312.

The above description and drawings are only to be considered illustrative of specific embodiments, which achieve the features and advantages described herein. Modifications and substitutions to specific process conditions can be made. Accordingly, the embodiments of the invention are not considered as being limited by the foregoing description and drawings.

What is claimed is:

1. A circuit for reducing common source inductance between paralleled transistors, comprising:

- a first transistor;
- a second transistor connected in parallel with the first transistor;
- a third transistor;
- a fourth transistor connected in parallel with the third transistor;

wherein a first pair of the four transistors are arranged such that their respective gates are oriented adjacent from each other and a second pair of the four transistors are arranged such that their respective gates are oriented adjacent from each other;

a first gate transfer line electrically coupling the gates of the first pair of transistors, the first gate transfer line running perpendicular to the output current path of the circuit; and

a second gate transfer line electrically coupling the gates of the second pair of transistors, the second gate transfer line running perpendicular to the output current path, wherein the arrangement and electrical coupling of the gates of the transistors provides a perpendicular spatial separation between the output current path and common

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source induction current path, the spatial separation decoupling the common source induction current path from the output current path, thereby reducing the common source inductance between the transistors.

2. The circuit of claim 1, wherein the first and second transistors are gallium nitride transistors.

3. The circuit of claim 1, wherein the first and second transistors are silicon transistors.

4. The circuit of claim 1, wherein the output current path is perpendicular to a current path of the common source inductance of the circuit.

5. The circuit of claim 1, wherein the first and second transistors experience a substantially equal voltage shift at a common gate connection as a result of a shift in an output current of the circuit.

6. The circuit of claim 1, wherein the first and second transistors are arranged widthwise to one another with the same orientation.

7. The circuit of claim 1, wherein the first and second transistors are arranged lengthwise to one another with opposing orientations.

8. The circuit of claim 1, wherein the third and fourth transistors have a common gate connection.

9. The circuit of claim 8, wherein the first and second transistors are arranged widthwise to one another, and the third and fourth transistors are arranged widthwise to one another.

10. The circuit of claim 1, wherein the first gate transfer line is coupled to the gates of the first and second transistors in a T structure configuration.

11. The circuit of claim 1, wherein the first gate transfer line is coupled to the gates of the first and second transistors in an H structure configuration.

12. The circuit of claim 1, wherein the first gate transfer line is coupled to the gates of the first and second transistors in an S structure configuration.

13. The circuit of claim 1, wherein a first distance from the gate driver transfer line to an output node of the circuit is greater than a second distance spanning the combined widths of the first and second transistors.

14. The circuit of claim 1, wherein the output current path comprises a first supply-to-load current path from the first transistor to the output node and a second supply-to-load current path from the second transistor to the output node.

15. The circuit of claim 8, wherein the output current path comprises:

- a first supply-to-load current path from the first transistor to the output node;
- a second supply-to-load current path from the second transistor to the output node;
- a first return-to-load current path from the third transistor to the output node; and
- a second supply-to-load current path from the fourth transistor to the output node.

16. The circuit of claim 1, wherein a parasitic inductance at a source of the first transistor has substantially the same magnitude as a parasitic inductance at a source of the second transistor.

17. The circuit of claim 16, wherein a voltage resulting from the output current on the parasitic inductance at the source of the first transistor has a substantially equal magnitude as a voltage resulting from the output current on the parasitic inductance at the source of the second transistor.

18. The circuit of claim 1, further comprising a decoupling element for decoupling the circuit from a power supply.

19. The circuit of claim 18, wherein the decoupling element is a capacitor.



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20. The circuit of claim 1, wherein the first and second transistors are arranged such that a distance between respective gates is less than three times the distance of the smallest physical dimension of the transistor devices.

21. The circuit of claim 1, wherein the first and second transistors include traces connected to the respective gate connections that are wider than the width of the gate connections.

22. A switching circuit for reducing common source inductance between paralleled transistors, comprising:

a plurality of upper transistors, each of said upper transistors comprising a respective source connection and drain connection and a common gate connection and at least two of the plurality of upper transistors being connected in parallel;

a plurality of lower transistors, each of said lower transistors comprising a respective source connection and drain connection and a common gate connection and at least two of the plurality of lower transistors being connected in parallel;

an output current node for outputting an output current of the switching circuit;

an upper switch gate connection line electrically connected to the common gate connection of the plurality of upper transistors wherein the upper switch gate connection line runs perpendicular to the output current;

a lower switch gate connection line electrically connected to the common gate connection of the plurality of lower transistors wherein the lower switch gate connection line runs perpendicular to the output current; and

wherein the upper transistors are arranged such that respective gates of the upper transistors are adjacent to each other and the lower transistors are arranged such that respective gates of the lower transistors are adjacent to each other,

wherein the arrangement and electrical connection of the gates of the transistors provides a perpendicular spatial separation between the output current and common source induction current, the spatial separation decoupling the common source induction current from the output current, thereby reducing the common source inductance between the transistors.

23. The switching circuit of claim 22, wherein at least one of the upper or lower pluralities of transistors is a gallium nitride transistor.

24. The switching circuit of claim 22, wherein the upper transistors are configured to experience a substantially equal voltage shift at the common gate connection of the upper transistors as a result of a current shift, and the lower transistors are configured to experience a substantially equal voltage shift at the common gate connection of the lower transistors as a result of a current shift.

25. The switching circuit of claim 22, wherein the circuit has an output current path with spatial separation from an inductance on the respective common gate connections of the upper and lower pluralities of transistors.

26. The switching circuit of claim 22, wherein the plurality of upper transistors includes a first transistor and a second transistor arranged in a same orientation and connected in parallel, and wherein the plurality of lower transistors includes a third transistor and a fourth transistor arranged in a same orientation and connected in parallel.

27. The switching circuit of claim 22, wherein the plurality of upper transistors includes a first transistor and a second transistor arranged in opposite orientations and connected in parallel, and wherein the plurality of lower transistors

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includes a third transistor and a fourth transistor arranged in opposite orientations and connected in parallel.

28. The switching circuit of claim 22, wherein the plurality of upper transistors includes a first transistor, a second transistor, and a third transistor connected at a common gate, and wherein the plurality of lower transistors includes a fourth transistor, a fifth transistor, and a sixth transistor arranged connected in parallel.

29. The switching circuit of claim 28, wherein the plurality of upper transistors further comprises a seventh transistor connected in parallel to the first, second, and third transistors, and wherein the plurality of lower switches further comprises an eighth transistor.

30. The switching circuit of claim 22, wherein the switching circuit is formed on a printed circuit board.

31. The switching circuit of claim 30, wherein a first set of the plurality of upper transistors is located on a first surface of the printed circuit board, and a second set of the plurality of upper transistors is located on a second surface of the printed circuit board.

32. The switching circuit of claim 30, wherein a first set of the plurality of lower transistors is located on a first surface of the printed circuit board, and a second set of the plurality of lower transistors is located on a second surface of the printed circuit board.

33. The switching circuit of claim 30, wherein the printed circuit board comprises a top surface, a bottom surface, and a plurality of internal layers.

34. The switching circuit of claim 33, wherein the upper switch gate connection line is formed between two electrically quiet internal layers.

35. The switching circuit of claim 33, wherein the lower switch gate connection line is formed between two electrically quiet internal layers.

36. The switching circuit of claim 22, further comprising at least one supply decoupling element.

37. The switching circuit of claim 36, wherein the supply decoupling element is a capacitor.

38. The switching circuit of claim 22, wherein the circuit is a converter.

39. The switching circuit of claim 22, wherein the circuit is an RF amplifier.

40. The switching circuit of claim 22, wherein the transistors are arranged such that a distance between adjacent gates is less than three times the distance of the smallest physical dimension of the transistor devices.

41. A method of forming a switching device with reduced common source inductance between paralleled transistors, said method comprising:

forming a first transistor having a first source, drain, and gate and a second transistor having a second source, drain, and gate on a printed circuit board;

forming a common gate connection and a common source connection for the first transistor and the second transistor;

forming a third transistor on the printed circuit board having a third gate;

forming a fourth transistor in parallel with the third transistor on the printed circuit board, the fourth transistor having a fourth gate;

wherein a first pair of the four transistors are arranged such that their respective gates are adjacent to one another and a second pair of the four transistors are arranged such that their respective gates are adjacent to one another;

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electrically coupling the respective gates of the first pair of transistors with a first gate connection driver line that runs perpendicular to an output current direction of the switching device; and

electrically coupling the respective gates of the second pair of transistors with a second gate connection driver line that runs perpendicular to the output current direction,

wherein the arrangement and electrical coupling of the gates of the transistors provides a perpendicular spatial separation between the output current direction and common source induction current direction, the spatial separation decoupling the common source induction current from the output current, thereby reducing the common source inductance between the transistors.

**42.** The method of claim **41**, wherein the first transistor and the second transistor are formed on a surface of a printed circuit board.

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**43.** The method of claim **41**, further comprising: forming a gate connection driver line electrically connected to the common gate connection of the first and second transistor.

**44.** The method of claim **41**, wherein the third transistor and the fourth transistor have forming a common gate connection and a common source connection.

**45.** The method of claim **44**, wherein the first gate connection driver line electrically connects to the common gate connection of the first and second transistors; and

the second gate connection driver line electrically connects to the common gate connection of the third and fourth transistors.

**46.** The method of claim **41**, wherein the transistors are arranged such that a distance between adjacent gates is less than three times the distance of the smallest physical dimension of the transistor devices.

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